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Space Station Resistojet System Requirements and Interface Definition Study

(NASA-CR-179581) SPACE STATICN RESISTOJET SYSTEM REQUIREMENTS AND INTERFACE DEFINITION STUDY Interim Report (Rockwell International Corp.) 88 p CSCL 21H N87-17848 Unclas G3/20 43333

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1.0 SUMMARY

An initial study of the resistojet assembly was conducted. Preliminary design requirements were established based upon initial technical requirements imposed by the results of NASA studies and Rocketdyne studies. The requirements are directed toward long life, simplicity, flexibility, and commonality with other Space Station components.

The resistojet assembly is comprised of eight resistojets, fluid components downstream of the waste fluid storage system, a power controller, structure, and shielding. The assembly consists of two identical subassemblies, one of which is redundant. Each subassembly consists of four 500-W resistojets, series redundant latch valves, a power controller, a water vaporizer, two pressure regulators, filters, check valves, disconnects, fluid tubing, and electrical cables. All components are packaged at the end of the stinger aft of the JEM and Columbus modules.

Different flow and power control methods were studied. A constant inlet pressure and a two-power setting controller were tentatively selected based upon simplicity and reasonably high specific impulse for the range of waste gas compositions that are anticipated. The constant pressure is supplied by pressure regulators. The two set point power control includes individual power supplies to each resistojet heater and water vaporizer. An embedded data processor, a multiplexer-demultiplexer, and a network interface unit that are standard Space Station components are included in the power controller.

The total dry weight of the resistojet assembly is approximately 172 lb. The total cost for design, development, test, evaluation, qualification, and flight hardware is estimated to be $16 million.

Recommended additional studies to be conducted prior to Phase C/D are:

- Conceptual design and analyses of resistojet assembly
- Control system study
- Cost update

2.0 INTRODUCTION

The function of the resistojet assembly is to generate as much as possible of the impulse required to offset atmospheric drag by disposal of as much as possible of the waste fluids on the Space Station. The resistojet assembly reduces the propulsion requirements and provides a backup for the high-thrust O_2/H_2 propulsion system, while reducing the overall operational cost of the Space Station by minimizing the quantity of waste fluids that must be brought back to earth.

A cold-gas disposal system could provide the same functions as the resistojet assembly without incurring the costs associated with design, fabrication, and test of resistojets and power controllers. However, the resistojet assembly offers major advantages over a cold-gas system that offset the higher initial cost. The resistojet assembly provides over two times the impulse for the same quantity of fluid. Heating the waste fluids prior to expansion through a high area ratio nozzle, which is the function of the resistojet, eliminates two-phase flow of waste gas in the nozzle. Two-phase flow can result in particulate matter sticking to Space Station surfaces. In addition, the heated flow in the high area ratio nozzle can be accelerated to, or near, free molecular flow which nearly eliminates backflow and minimizes contamination of the local environment.

The objective of the study that is reported was to (1) establish preliminary technical and design requirements for the resistojet assembly, (2) define interfaces, (3) develop a design concept, and (4) identify candidate components of the assembly. The effort was conducted during June to October 1986.

3.0 TECHNICAL REQUIREMENTS

Primary technical requirements for the resistojet assembly, which have been defined by initial NASA and contractor studies, are summarized in this section. These evolving requirements are intended for inclusion in the top-level specification for the resistojet assembly presented in the Appendix. The following technical requirements have been used in defining the preliminary resistojet assembly.

3.1 FLUIDS

The waste fluids include argon, carbon dioxide, carbon dioxide/methane mixtures, helium, hydrogen, nitrogen, krypton, water, oxygen, and cabin air. Contaminant species are undefined.[1]

The resistojet assembly must accept all non-toxic, non-particulate containing waste gases, both as mixtures and as single species, as defined in Table 1 for 90 day accumulations for the IOC and growth Space Stations.[1] Quantities of water, oxidizers, and contaminants are as yet undefined.

The fluid levels based upon the Bosch ECLSS are baselined, A final selection between the Bosch and Sabatier processes will be made by mid-1987.

3.2 POWER

The maximum power required by the resistojet assembly during operation shall not exceed 2 kW.

3.3 LIFE

The resistojet assembly shall be designed to require no scheduled maintenance for at least a 10-year period in space. The operating life shall be at least 10,000 h.

3.4 EVA

The design of the resistojet assembly shall minimize EVA time for deployment and (nonscheduled) maintenance.

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[1]R. Tacina et al., "Conceptual Design and Integrations of a Resistojet Module Aboard the I.O.C. Space Station," NASA-LeRC, DIR 159, 24 July 1986.

TABLE 1

WASTE GAS SUMMARY
(lbm per 90 days)

FLUID	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
(SABATIER)										
ARGON	403.2	415.5	427.8	440.2	452.2	463.6	475.9	488.2	500.4	512.7
CO2	149.9	167.6	185.1	202.6	220.6	237.6	255.6	273.6	290.6	308.6
HELIUM	78.8	87.4	96.0	104.6	113.2	121.9	130.5	139.1	147.8	156.3
HYDROGEN	35.7	40.0	44.5	48.8	53.1	57.6	61.9	66.2	70.7	75.0
CO2/METHANE	935	1169	1169	1403	1403	1636	1636	1870	1870	2104
NITROGEN	458	514.7	570.3	627	682.7	739.3	795	851.7	907.3	964
KRYPTON	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8
TOTALS:	2080.4	2414.0	2512.5	2846.0	2944.6	3275.8	3374.7	3708.6	3806.6	4140.4

FLUID	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
(BOSCH ECLSS)										
ARGON	403.2	415.5	427.8	440.2	452.2	463.6	475.9	488.2	500.4	512.7
CO2	149.9	167.6	185.1	202.6	220.6	237.6	255.6	273.6	290.6	308.6
HELIUM	78.8	87.4	96.0	104.6	113.2	121.9	130.5	139.1	147.8	156.3
HYDROGEN	77.1	91.8	96.4	110.9	115.2	130.1	134.4	149.0	153.5	168.2
NITROGEN	458	514.7	570.3	627	682.7	739.3	795	851.7	907.3	964
KRYPTON	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8
TOTALS:	1186.8	1296.8	1395.4	1505.1	1603.7	1712.3	1811.2	1921.4	2019.4	2129.6

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4.0 RESISTOJET ASSEMBLY DESIGN

Based on the NASA- and Rocketdyne-imposed technical requirements, the following preliminary overall design requirements were established:

- The resistojet assembly shall be as simple as possible, consistent with meeting life and reliability requirements. Specific impulse performance shall be compromised if necessary to provide simplicity and reduced parts count.

- The resistojet assembly will be comprised of components with minimum development requirements. Wherever practical, components and concepts that are common with other Space Station systems will be incorporated in the resistojet assembly. For example, if the waste fluid management system incorporates 1/2-in. latching valves of a specific concept, this same concept will be incorporated, if practical, for 1/4-in. or 1/8-in. valves in the resistojet assembly. This should reduce overall cost to the Space Station program by reducing development and qualification cost by the selected supplier(s).

- Each resistojet must be capable of accepting reducing gas mixtures, oxidizing gas mixtures, and steam (but not simultaneously). Individual resistojets will not be dedicated to a given class of fluids. This requirement increases redundancy.

The waste fluids are supplied to the resistojet assembly by the integrated waste fluid management system (WFMS), which consists of a collection subsystem and a storage subsystem. A simplified schematic of the WFMS is shown in Fig. 1. The fluid interface of the resistojet assembly with the storage subsystem is just downstream of the parallel redundant shutoff valves for reducing gases, nonoxidizing gases, and water in the storage subsystem. All components downstream of the storage system shutoff valves are included in the resistojet assembly. The storage system shutoff valves are assumed to be included in the assembly upstream of the boom. The resistojet assembly includes disconnects, fluid lines and electrical lines along the boom.

A preliminary definition of the resistojet assembly is shown in Fig. 2. The assembly consists of two identical subassemblies, one of which is redundant. Each subassembly consists of four 500-W resistojets, a power controller, a water vaporizer, a pressure regulator, series redundant latch valves, filters, check valves, and disconnects. All components are close-coupled. Figures 3 and 4 illustrate packaging concepts. In Fig. 3, the redundant latching valves are mounted on the power controller chassis, which results in a minimum size assembly. Other fluid components are located behind the power controller. In Fig. 4, the redundant latch valves are located between the resistojets and the power controller. This arrangement will provide better thermal isolation of the controller from the resistojets, at an increased dimensional envelope. Detailed thermal analysis is required to select the most suitable packaging concept.

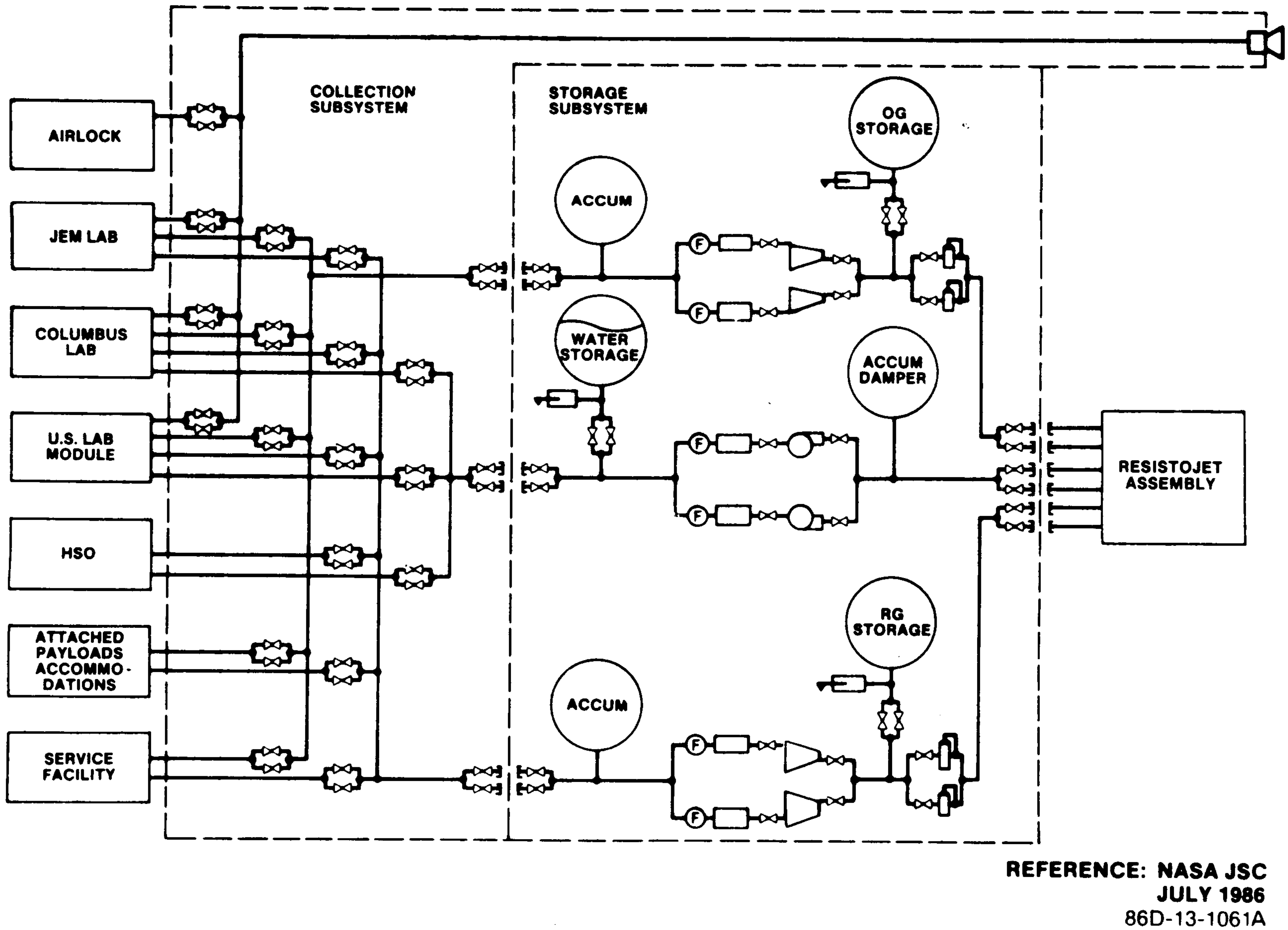

Figure 1. Integrated Waste Fluid Management System Schematic

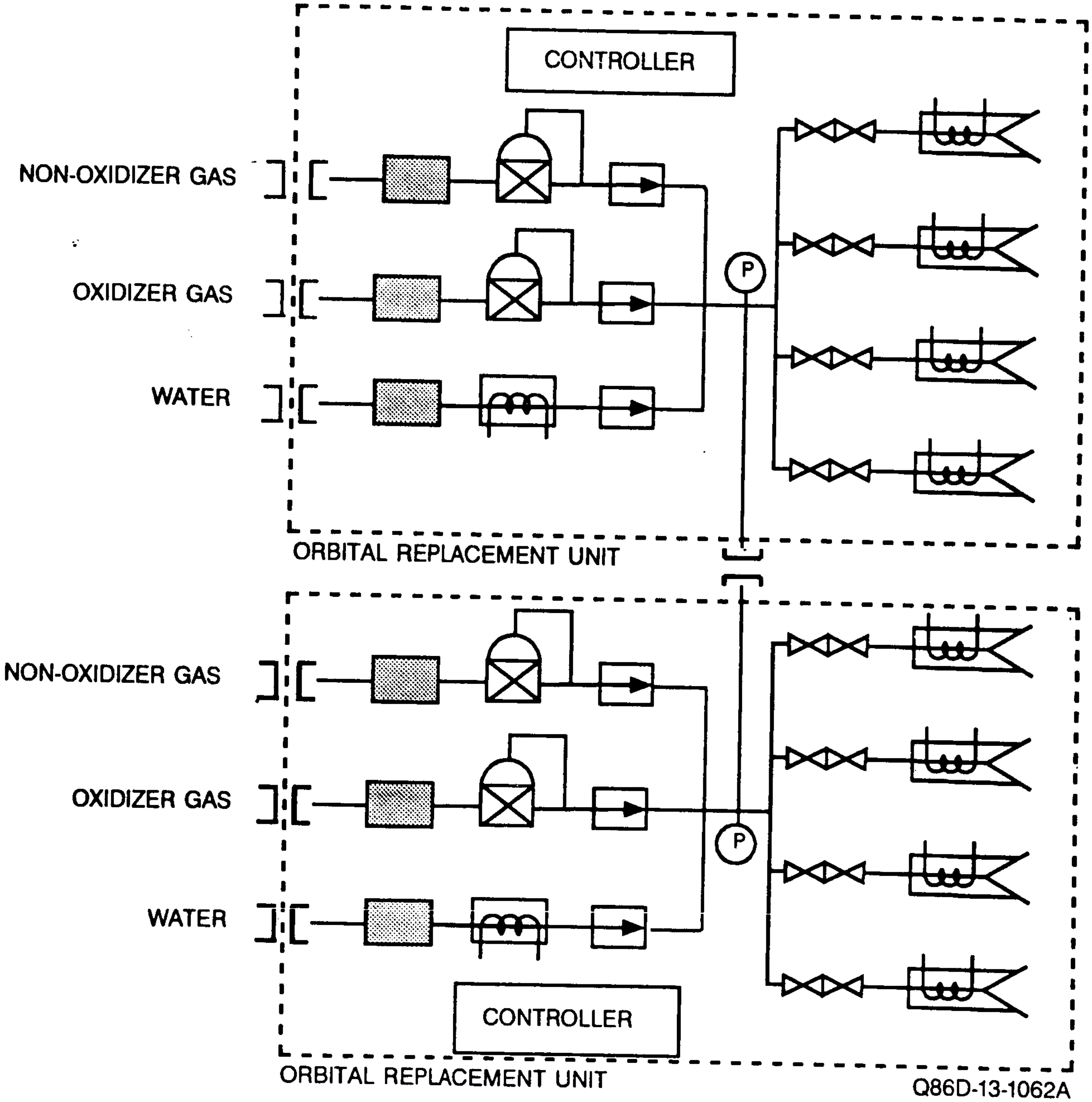

Figure 2. Resistojet Assembly

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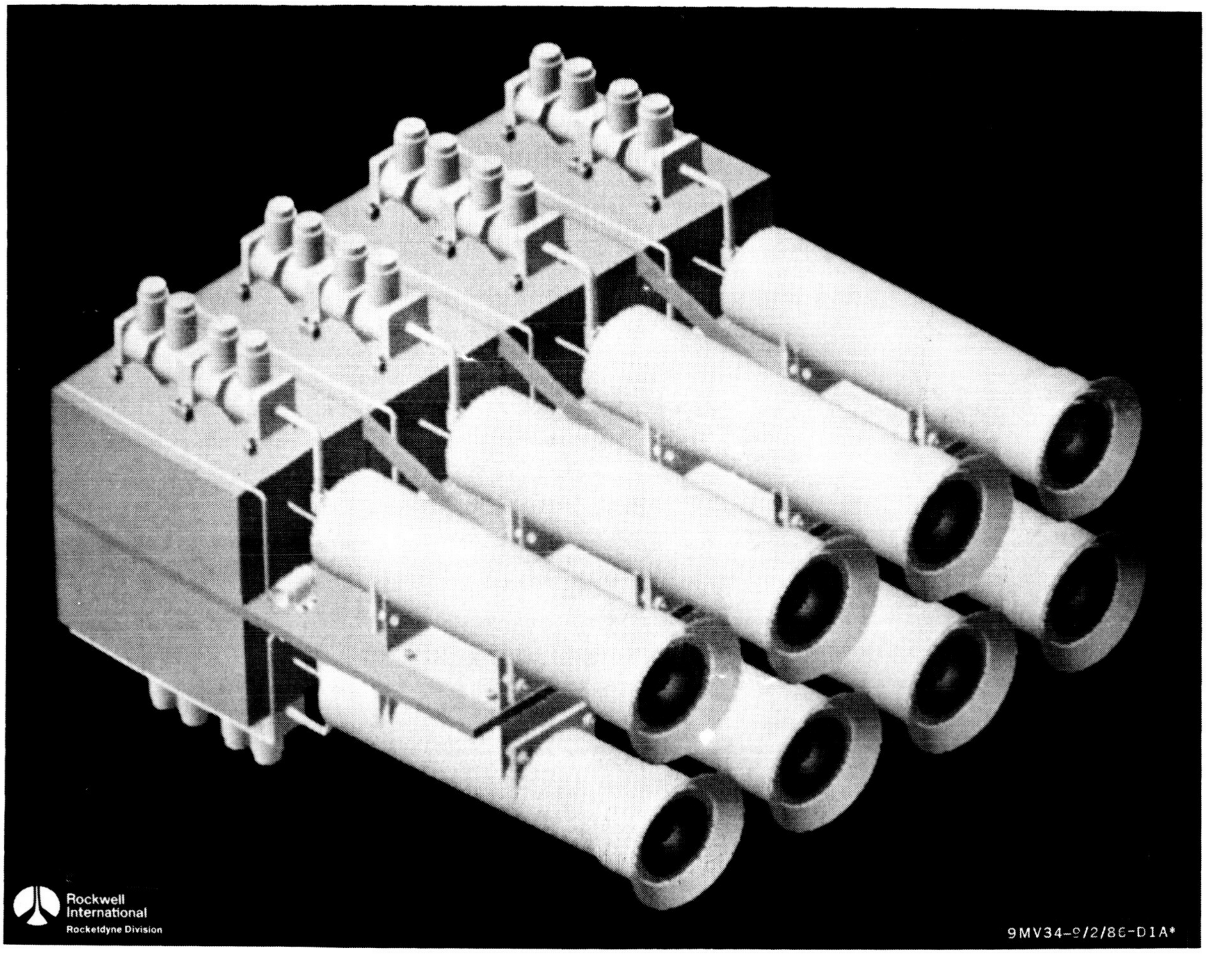

Figure 3. Resistojet Assembly, with Valves Mounted on Power Control Enclosure

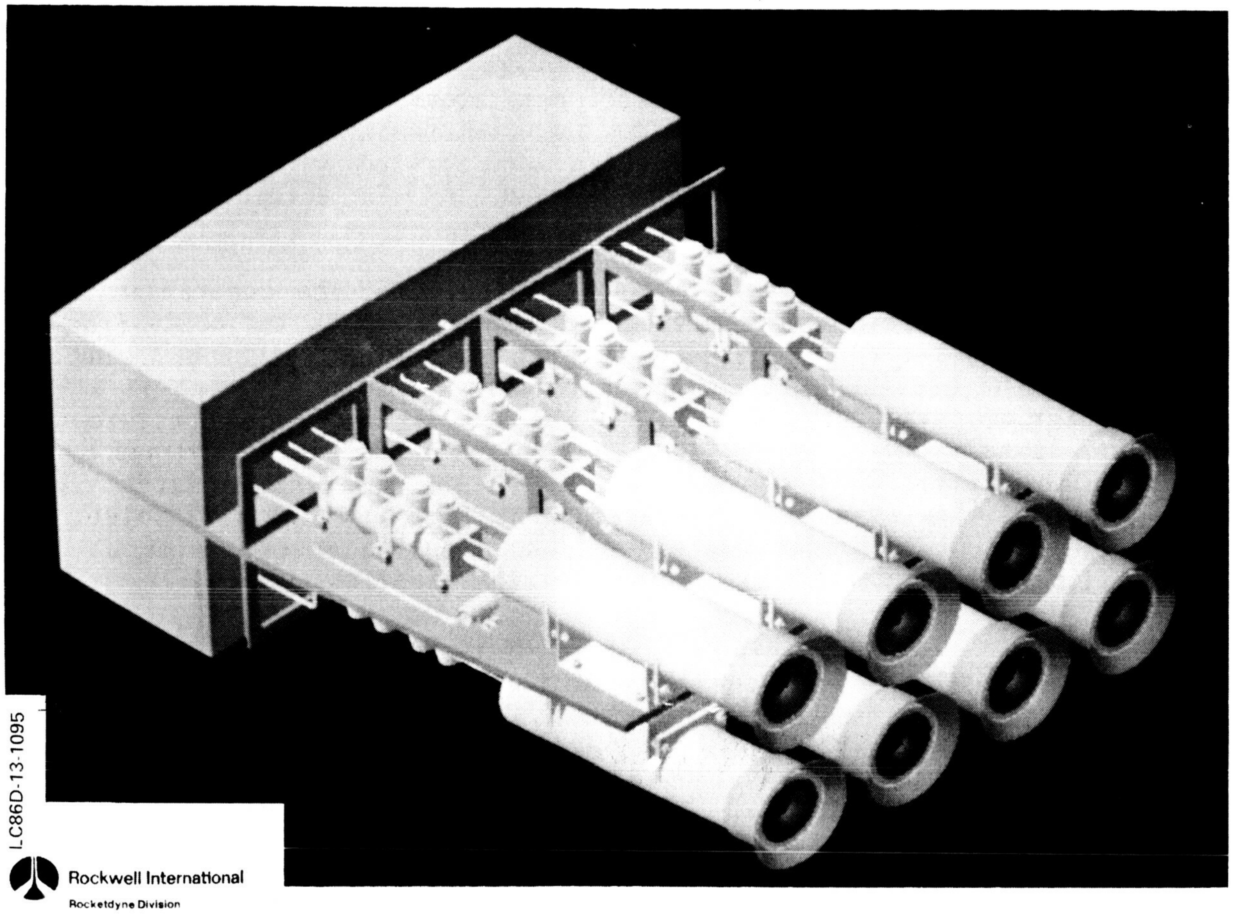

Figure 4. Resistojet Assembly, with Valves on Resistojet Mount Plate

The packaging concept allows replacement of one complete subassembly, if required. One fluid connection and one electrical wire harness connect the two subassemblies (Fig. 2). This allows operation of resistojets in the redundant subassembly using the flow control in the primary subassembly in the event of resistojet malfunction in the primary subassembly. Up to four resistojets will be operated simultaneously. Thus, increased flexibility is gained at the expense of pressurizing the redundant subassembly while the primary subassembly is operating. An additional valve in each subassembly at the disconnect between the subassemblies could be added to eliminate pressurization of the redundant subassembly.

The resistojet assembly incorporates pressure regulators for flow control of the gases. Water flow is controlled by the pumps in the WFMS storage subsystem. Low-capacity, low-micron filters are incorporated at each fluid disconnect. The high-volume filtration, if needed, will be accomplished in the collection or storage subsystems.

One controller is used for each set of four resistojets. The controller operates the resistojet heaters, water vaporizer, and valves, with inputs from the data management system (DMS), guidance navigation and control (GN&C), and health monitors. The health monitors measure heater resistance, which is a function of heater temperature, and pressure, which is a function of resistojet flow and pressure regulator operation. Heater resistance is determined by measurement of the voltage and current for each heater element. Heater resistance indicates flow as well as temperature for an operating resistojet. An indication of out-of-tolerance heater resistance during operation of a resistojet will be used to terminate operation of that resistojet.

A parts count for the resistojet assembly is shown in Table 2. A third subassembly is included for an orbital replacement unit (ORU).

The WFMS as shown includes three sets of tanks to separate reducing gas, oxidizing gases, and water. An additional set of tanks will be required if the waste gas includes hydrocarbons. The resistojet heat exchanger temperature must be reduced to approximately 500°C for operation with hydrocarbons to preclude decomposition and coking of the heat exchanger surfaces. Thus, specific impulse performance is reduced for operation with hydrocarbons. If the hydrocarbons are stored in the same tanks as the reducing gases, then the total quantity of waste gas would be utilized at significantly reduced specific impulse. An alternative, which is under study, is to react all the waste gases and store the filtered reactants in a single set of tanks. If this proves to be the optimum system, one of the two pressure-regulated fluid lines in each subassembly shown in Fig. 2 can be eliminated.

TABLE 2
RESISTOJET PROPULSION MODULE COMPONENTS

	QUANTITY PER SUBASSEMBLY	TOTAL ON STATION
RESISTOJET	4	12
CONTROLLER	1	3
LATCH VALVE	8	24
CHECK VALVE	3	9
PRESSURE REGULATOR	2	6
WATER VAPORIZER	1	3
FILTER	3	9
DISCONNECT	4	12
MANIFOLDING AND TUBING	1	3
CABLES AND WIRING	1	3
STRUCTURE	1	3
THERMAL SHIELDING	1	3
PRESSURE TRANSDUCER	2	3

ONE SUBASSEMBLY PLUS ONE REDUNDANT SUBASSEMBLY COMPRISE THE RESISTOJET ASSEMBLY. A THIRD SUBASSEMBLY IS INCLUDED AS AN ORBITAL REPLACEMENT UNIT.

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5.0 CONTROL AND PERFORMANCE PARAMETERS

Overall control requirements are summarized in Table 3. This section compares candidate flow and power control methods to arrive at a preliminary selection.

The temperature of the resistojet heater must be maintained below a maximum temperature of 1400°C to achieve an operational life in excess of 10,000 h. If the waste life gas contains methane or other hydrocarbons, the heat exchanger temperature must be reduced well below this value to prevent carbon deposition on the heat exchanger surfaces. Operation at the maximum allowable temperature will result in the maximum specific impulse for any gas composition. Since the gas heat input equivalent to the power input is

$$q = \dot{W}_g C_{pg}(T_{g,out} - T_{g,in})$$

the power required to reach a heater temperature of 1400°C, which is only slightly higher than the gas outlet temperature, is a function of the gas flowrate ($\dot{W}_g$) and specific heat (C_{pg}).

The waste gas species will vary during operation; consequently, the specific heat of the gas flow and the power required to bring the heater temperature up to 1400°C will vary. Different control methods, summarized in Table 4, are potentially applicable, which constitute a trade between maximum specific impulse performance and complexity.

The candidate control methods can be grouped into two categories (Fig. 5): the inlet pressure can be maintained constant with fixed, variable, or multiple power settings; or the flow can be varied and the power maintained constant. A feedback signal that is indicative of heater temperature is required for any power and flow control method. The simplest power and flow control method consists of maintaining constant power and constant inlet pressure regardless of waste gas composition. A pressure setting would be selected for a nominal gas composition (Table 5) that results in a 1400°C heater temperature at 500 W. For all other gas compositions, the temperature and specific impulse would be reduced. For gas compositions with lower specific heat than the nominal, the power would need to be turned off or the heater temperature would exceed 1400°C. Thus, the power would have to be turned off for all gas compositions except for the nominal mixed gas composition, those with higher than nominal levels of hydrogen or helium, and for steam. The constant power and constant inlet pressure control method is therefore unacceptable.

Maintaining a constant inlet pressure and varying the power to provide a 1400°C outlet gas temperature provides maximum specific impulse for all gas compositions. However, the required power varies from 185 W for krypton, which has the lowest specific heat, to 1564 W for hydrogen, which has the highest specific heat (Table 6). This method requires the most sophisticated power controller.

TABLE 3
CONTROL REQUIREMENTS

1. **LIMIT MAXIMUM HEATER TEMPERATURE TO 1400°C**
2. **LIMIT MAXIMUM HEATER TEMPERATURE TO ~500°C IF RESISTOJETS OPERATE ON WASTE GAS WITH HYDROCARBON**
3. **SELECT HOW MANY AND WHICH RESISTOJETS TO TURN ON**
4. **TURN ON WATER VAPORIZER HEATER AND SELECT POWER SETTING WHEN RESISTOJETS OPERATE ON WATER**
5. **TURN OFF RESISTOJETS IF HEALTH MONITORS INDICATE PERFORMANCE DEGRADATION**
6. **CONVERT INPUT POWER AND SIGNALS TO USEABLE CONDITIONS FOR MODULE**
7. **ACCEPT WASTE GAS WITH VARIABLE COMPOSITION**

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TABLE 4
RESISTOJET HEATER CONTROL METHODS

1. **CONSTANT POWER AND FIXED INLET PRESSURE**
   - OUTLET GAS TEMPERATURE WILL VARY, WITH Isp DEGRADATION, FOR OFF-NOMINAL GAS COMPOSITION

   $q = \dot{\omega}\, Cp\, (T_C - T_{IN})$
   $Cp = fn$ (GAS COMPOSITION)
   $\dot{\omega} = C_D A\, fn(M, \gamma)\, Pc/\sqrt{T_C}$
   $P_{IN} \simeq Pc$

2. **CONSTANT INLET PRESSURE AND VARIABLE POWER**
   - OUTLET GAS TEMPERATURE CAN BE MAINTAINED AT 1400°C FOR MAXIMUM Isp
3. **CONSTANT INLET PRESSURE AND TWO POWER SETTINGS**
   - ~1400°C CAN BE OBTAINED FOR NOMINAL COMPOSITION CO_2, ARGON, STEAM; REDUCED TEMPERATURE FOR PURE He, H_2, O_2, N_2, KRYPTON
4. **CONSTANT POWER AND VARIABLE FLOW CONTROL**
   - OUTLET GAS TEMPERATURE CAN BE MAINTAINED AT 1400°F FOR MAXIMUM Isp

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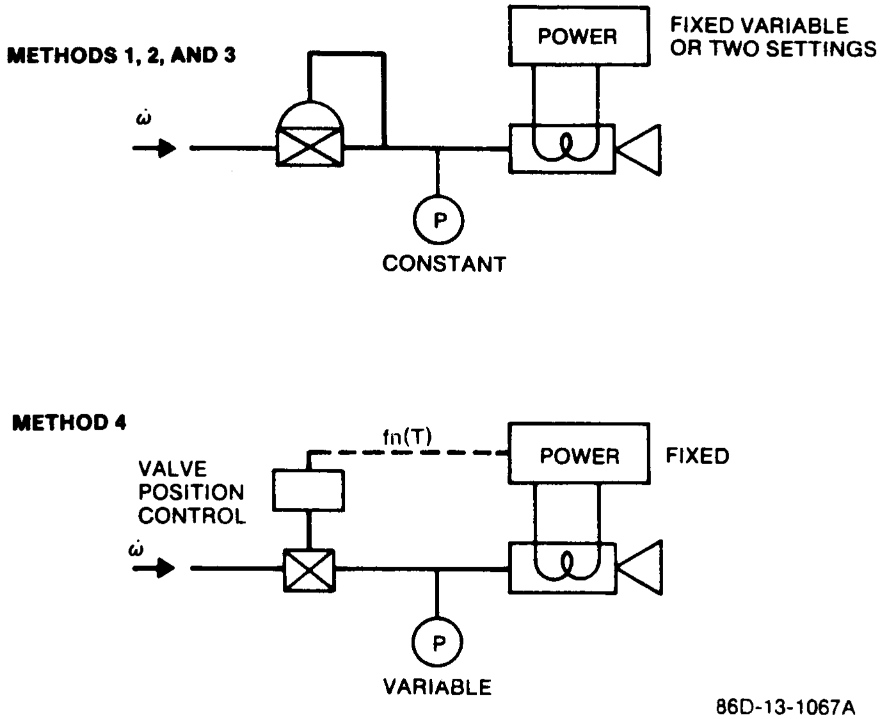

Figure 5. Control Methods

TABLE 5

WASTE GAS COMPOSITION (lbm per 90 days)

FLUID	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
(BOSCH ECLSS)										
ARGON	403.2	415.5	427.8	440.2	452.2	463.6	475.9	488.2	500.4	512.7
CO2	149.9	167.6	185.1	202.6	220.6	237.6	255.6	273.6	290.6	308.6
HELIUM	78.8	87.4	96.0	104.6	113.2	121.9	130.5	139.1	147.8	156.3
HYDROGEN	77.1	91.8	96.4	110.9	115.2	130.1	134.4	149.0	153.5	168.2
NITROGEN	458	514.7	570.3	627	682.7	739.3	795	851.7	907.3	964
KRYPTON	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8
TOTALS:	1186.8	1296.8	1395.4	1505.1	1603.7	1712.3	1811.2	1921.4	2019.4	2129.6

REFERENCE: NASA LeRC PIR NUMBER 159

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TABLE 6

RESISTOJET PERFORMANCE PARAMETERS FOR CONSTANT INLET PRESSURE AND VARIABLE POWER

P_{inlet} = 50 psia

FLUID	Isp (s)	$\dot{W}$ (lb/h)	POWER (W)	F (lbf)
ARGON	135	2.37	301	0.089
CO_2	140	2.28	600	0.082
HELIUM	425	0.74	836	0.087
HYDROGEN	500	0.50	1564	0.070
NITROGEN	160	1.87	459	0.083
KRYPTON	93	3.44	185	0.089
MIXED GASES	235	1.30	587	0.085
STEAM	200	1.45	726	0.081
O_2	150	2.00	436	0.083
CABIN AIR	157	1.90	449	0.083

$T_{GAS\ OUT}$ = 1400°C

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Maintaining a constant inlet pressure with a two-set-point power controller retains the basic simplicity of the fixed-setting power controller while providing reasonable specific impulse performance for low-specific heat fluids such as argon, nitrogen, and cabin air. Table 7 lists gas temperature, specific impulse, flow, and thrust for a power controller with set points of 500 and 250 W. The performance is tabulated for the nominal mixed gas composition, for the pure species that comprise the mixed gas, and for steam, oxygen, and cabin air.

The nominal design is based upon a power input of 500 W to provide a temperature of the nominal mixed gas composition of 1400°C. An inlet pressure of 40 psia is required. The high power setting is for carbon dioxide, helium, hydrogen, and steam, as well as the nominal mixed gas composition. The low-power setting is for the fluids with lower specific heat: argon, nitrogen, oxygen, and cabin air.

It is probable that the resistojets will not be required to operate on pure gas species. In operation, the resistojet heater voltage and temperature will be measured, which is an accurate measure of average heater temperature. If the heater temperature tends to exceed 1400°C, the power setting will be switched automatically to the lower value.

Maximum specific impulse performance for all gas compositions also can be achieved by maintaining constant power and varying the flow. Performance parameters for this control method are listed in Table 8. The inlet pressure varies from 15 psia for hydrogen to 82 psia for argon. The thrust varies from 0.022 lbf for hydrogen to 0.148 lbf for argon. For this method, the pressure regulator is replaced by a flow control valve, the opening of which is controlled by a feedback signal that is a function of resistojet heater temperature.

A comparison of the four control methods is summarized in Table 9. The constant pressure and two-power setting control method is tentatively selected. If maximum specific impulse is found to be necessary to meet impulse requirements, then a constant power control with variable flow control would be selected.

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TABLE 7

RESISTOJET PERFORMANCE PARAMETERS FOR CONSTANT INLET PRESSURE, TWO POWER SETTINGS

$P_{in.}$ = 40 psia

FLUID	INPUT POWER (W)	T_{GAS} (°C)	$\dot{W}$ (lb/h)	Isp (s)	F (lbf)
ARGON	250	1400	1.96	135	0.074
CO_2	500	1370	1.94	130	0.070
HELIUM	500	850	0.74	348	0.072
HYDROGEN	500	380	0.61	312	0.053
NITROGEN	250	750	1.92	125	0.067
KRYPTON	0	20	5.27	40	0.059
MIXED GASES	500	1400	1.11	235	0.072
STEAM	500	1200	1.31	188	0.068
O_2	250	725	2.10	115	0.068
CABIN AIR	250	740	1.95	122	0.066

C_DA = 0.00125 $in.^2$

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TABLE 8

PRELIMINARY RESISTOJET PERFORMANCE PARAMETERS FOR CONSTANT POWER AND VARIABLE FLOW

POWER = 500 W

FLUID	Isp (s)	$\dot{W}$ (lb/h)	P_{INLET} (psia)	F (lbf)
ARGON	135	3.93	82	0.148
CO_2	130	1.89	38	0.068
HELIUM	425	0.44	30	0.052
HYDROGEN	500	0.16	15	0.022
NITROGEN	160	2.04	54	0.091
MIXED GASES	235	1.11	40	0.072
STEAM	200	1.00	34	0.056

$T_{GAS\ OUT}$ = 1400°C

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TABLE 9

COMPARISON OF CONTROL METHODS

METHOD	ADVANTAGES	DISADVANTAGES
1. CONSTANT POWER AND FIXED PRESSURE	SIMPLEST	Isp DEGRADATION
2. CONSTANT PRESSURE AND VARIABLE POWER	OPTIMUM Isp FOR ALL GAS COMPOSITIONS	MOST COMPLICATED POWER CONTROL
3.* CONSTANT PRESSURE AND TWO-POWER SETTING	OPTIMUM Isp FOR NOMINAL GAS COMPOSITION AND PURE CO_2, STEAM AND ARGON; RETAINS POWER CONTROL SIMPLICITY	Isp DEGRADATION FOR PURE He, H_2, O_2, N_2, AND KRYPTON
4. CONSTANT POWER AND VARIABLE FLOW CONTROL	OPTIMUM Isp FOR ALL GAS COMPOSITIONS	FLOW CONTROL MORE COMPLICATED THAN CONSTANT PRESSURE REGULATION

*PRELIMINARY SELECTION

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6.0 COMPONENT DESCRIPTION

This section describes major components of the resistojet assembly. The components include the resistojet, the controller, the water vaporizer, the latch valve, the pressure regulator, manifolds, and tubing.

6.1 RESISTOJET

The function of the multi-propellant resistojet is to provide thrust by heating a variety of nonreactive gases, either of single or mixed species, and expanding the heated gas through a high area ratio nozzle. The high area ratio nozzle will expand the heated gas to, or close to, the free molecular flow regime, which eliminates or minimizes backflow at the nozzle exit and resulting contamination of the Space Station surfaces and the local environment. Heating the gas to sufficiently high temperature prevents condensation of low-velocity particulates in the nozzle that would stick to adjacent surfaces.

The multi-propellant resistojet (Figs. 6 and 7) consists of an electrical heater, a fluid heat exchanger, a high area ratio nozzle, and thermal insulation. An engineering model of the resistojet is currently being designed and fabricated by Technion Incorporated under subcontract to Rocketdyne under Contract NAS3-24658. Testing and evaluation of the resistojet are being conducted by NASA-LeRC. Design parameters are listed in Table 10.

The heat exchanger, the nozzle, and inner radiation shielding are constructed of grain-stabilized platinum. Platinum is specified for the design because it is the most compatible uncoated metal for long-life operation with the waste gases propellants. Grain stabilization improves the creep-rupture strength properties of platinum.

The heater element consists of a platinum center conductor, magnesium oxide insulation, and an outer grain-stabilized platinum sheath. The heating element is coiled around the heat exchanger shell (Fig. 8). Good thermal contact between the heating element and the shell is obtained by diffusion bonding the heating element to the shell. The gas is heated by thermal conduction from the heater to the heat exchanger shell and convection from the shell to the gas. Thirty-six axial flow channels are machined into the shell. An inner cylinder closes out the flow channels.

The thermal insulation consists of 10 radiation shields. The outer case is constructed of Inconel. The resistojet as fabricated is shown in Fig. 9.

Nominal input power to the resistojet is 500 W. The resistojet is designed to operate for at least 10,000 h at a heater temperature of 1400°C without maintenance. The heater resistance versus temperature is shown in Fig. 10. Heater resistance is a primary health monitor used for control of the resistojet.

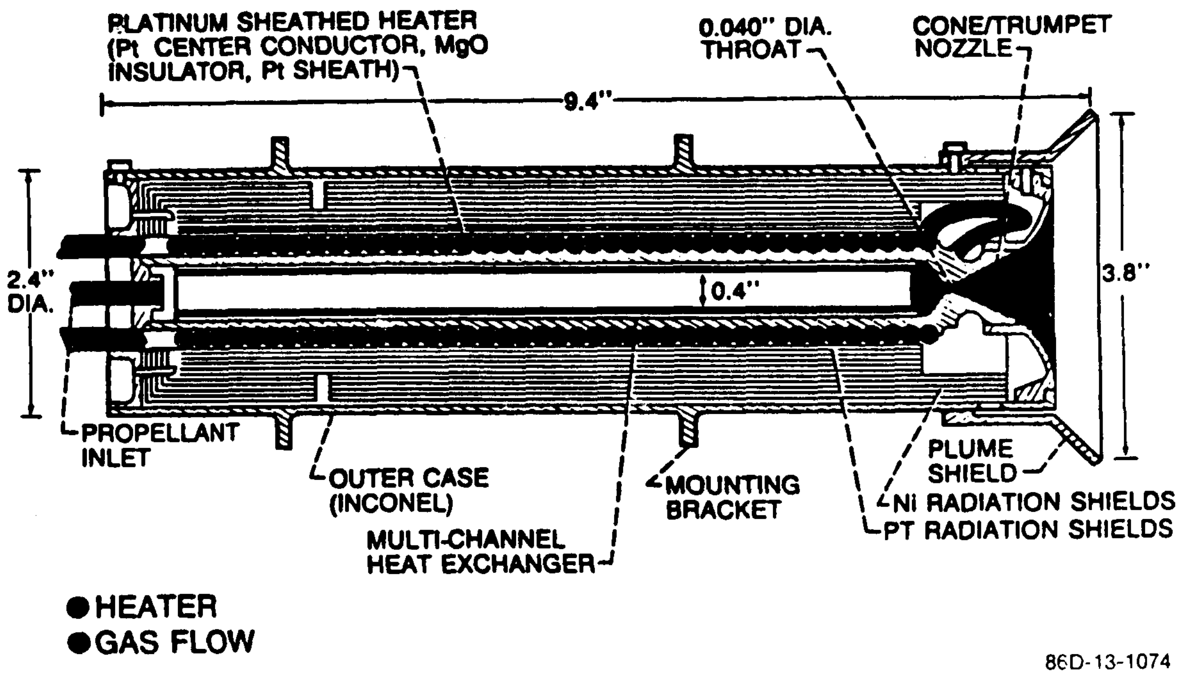

Figure 6. Advanced Development Engineering Model Resistojet

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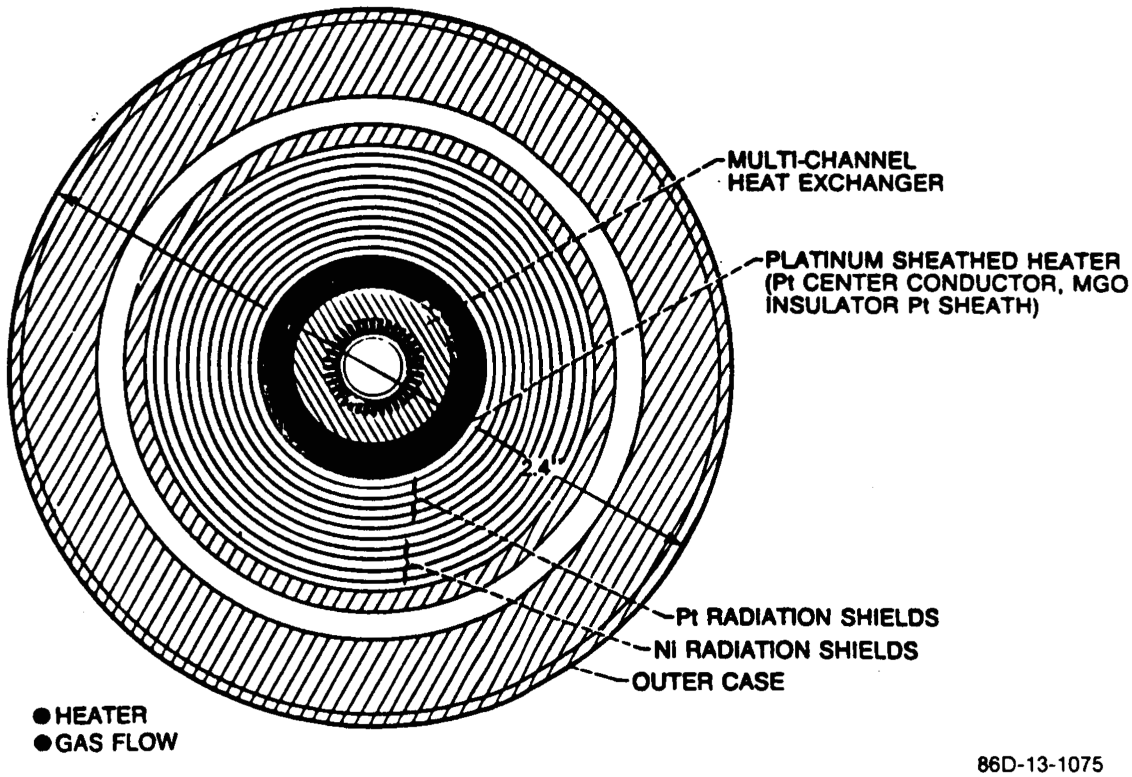

Figure 7. Advanced Development Engineering Model Resistojet Cross Section

TABLE 10

RESISTOJET DESIGN

SUPPLIER	TECHNION/ROCKETDYNE
PART NUMBER	T501050
HEATER	PLATINUM CENTER CONDUCTOR Pt-10% Rh, 0.062 in. DIAMETER PLATINUM SHEATH GSP, 0.156 in. OD, 0.019 in. WALL MgO INSULATION 0.028 in. THICKNESS 129 in. LONG BEFORE COILING
HEAT EXCHANGER	PLATINUM (GSP) 36 CHANNELS, 0.020 in. WIDE, 0.050 in. DEEP, 7.4 in. LONG
THERMAL INSULATION	10 RADIATION SHIELDS 5 — 0.001 in. THICK GSP 5 — 0.004 in. THICK NICKEL
OUTER CASE	INCONEL
MAXIMUM ELECTRICAL OPERATING PARAMETERS	
POWER (W)	500
RESISTANCE (Ω)	0.95
VOLTAGE	22
CURRENT	23
WEIGHT (lb)	8.0 INCLUDING MOUNT PLATE
ENVELOPE	3.8 in. DIAMETER, 9.4 in. LONG (EXCLUDING MOUNT)

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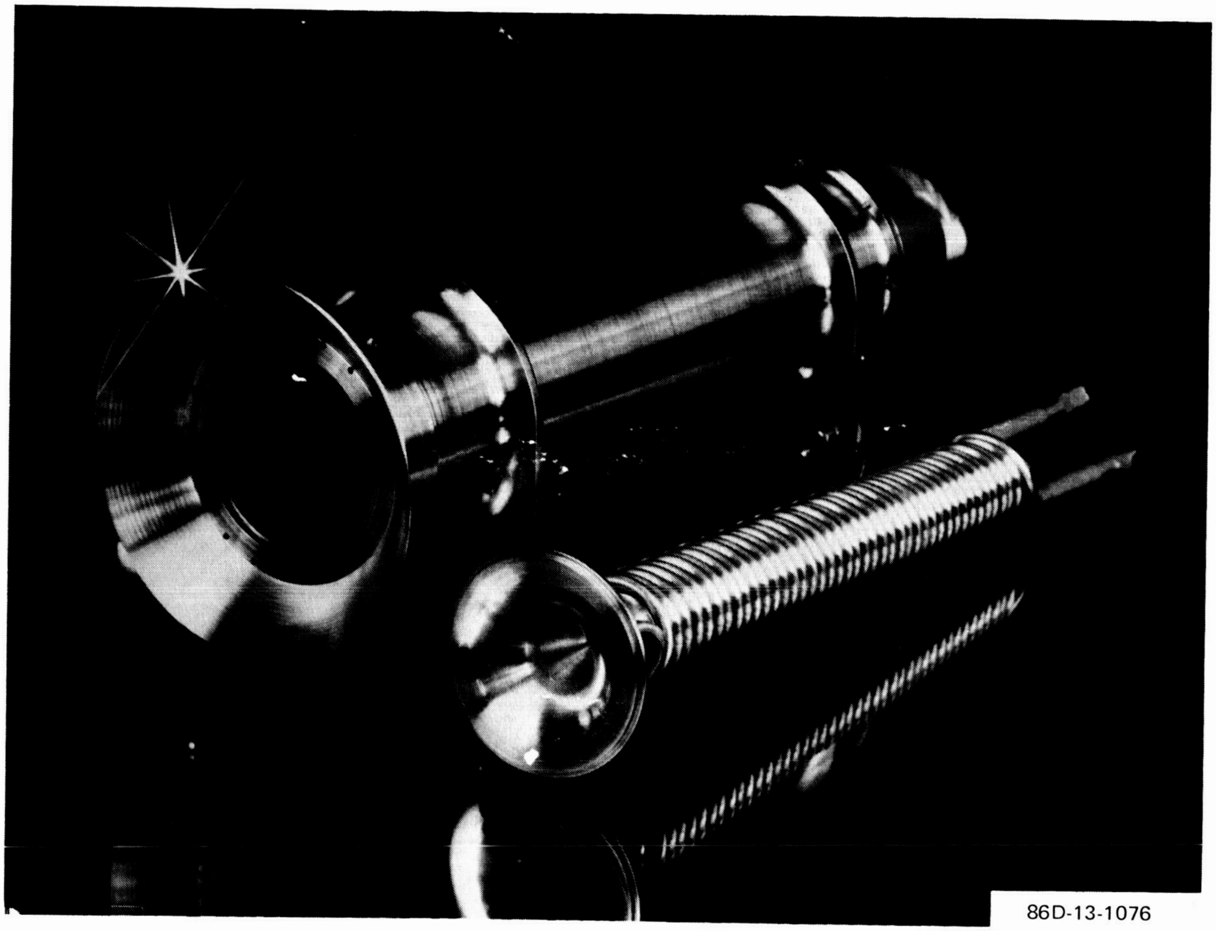

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Figure 8. Resistojet Heater Assembly

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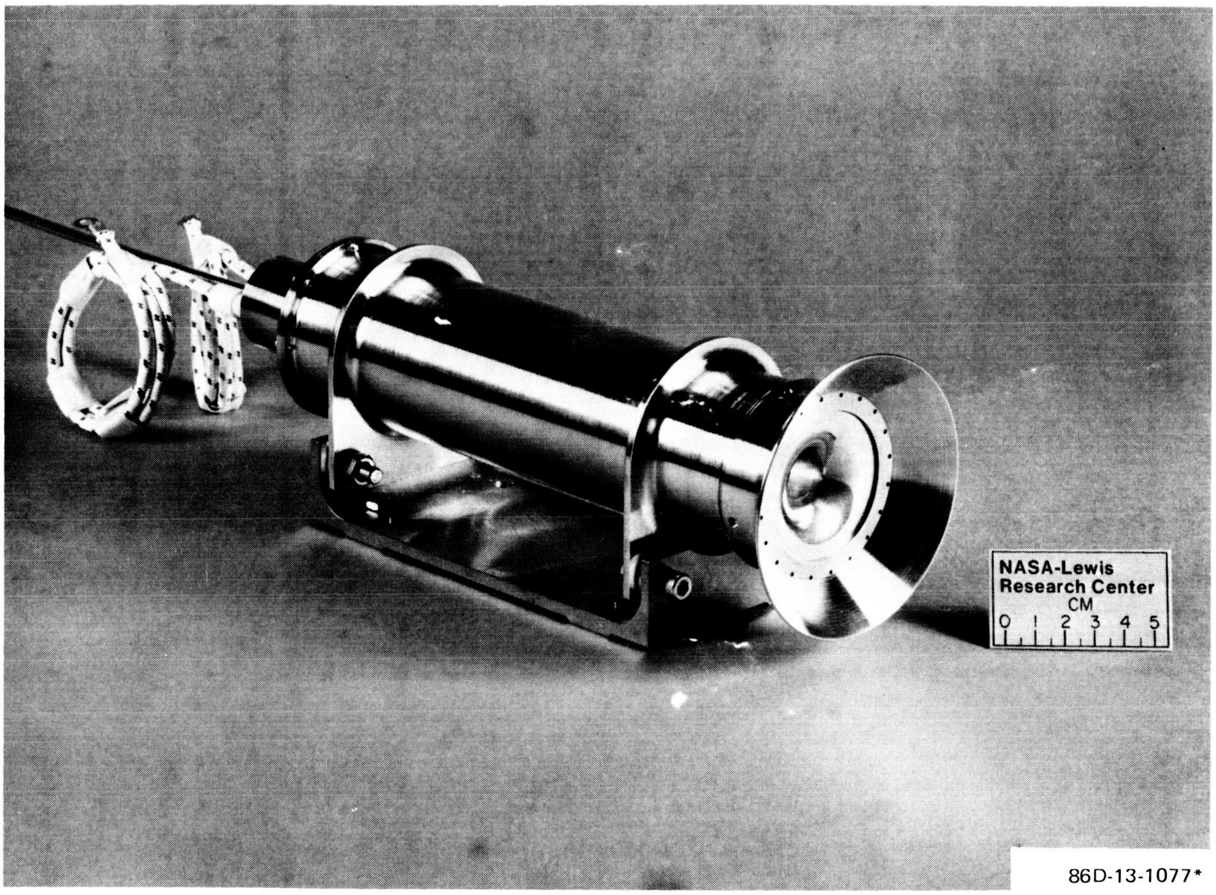

Figure 9. Multi-Propellant Resistojet

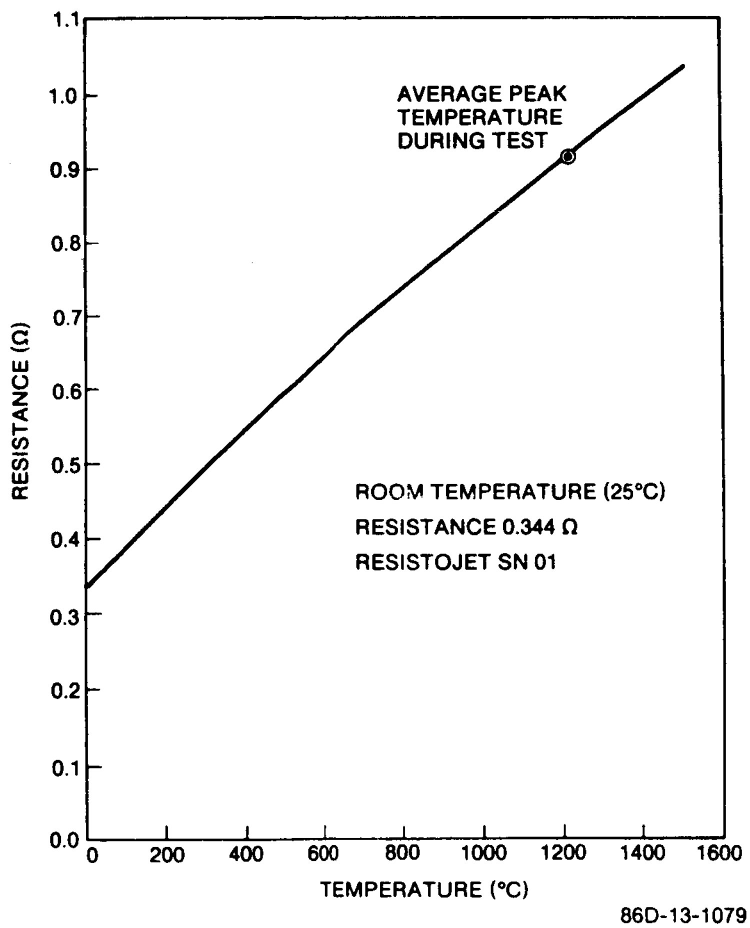

Figure 10. Heater Resistance

Power input to the resistojet heater element is 22 A at 20 kHz. A preliminary analysis was conducted to estimate the level of electro-magnetic interference generated within the resistojet. Based upon an estimate of 1 in. of uncompensated heater wire (without current in an adjacent wire in the opposite direction) contained in the heater wire loop near the nozzle, a magnetic induction corresponding to 102 dB above 1 pT was calculated. The MIL-STD 461BRE01 limit for magnetic induction is 26 dB above 1 pT.

The calculated value thus exceeds the specification. The effect of the resistojet thermal insulation and outer case, and the distance from the resistojets to sensitive equipment must be determined. If the magnetic induction is found to exceed actual requirements for user experiments, possible solutions include the following:

- Shield the resistojets with iron
- Shield the experiments
- Use a d-c power supply
- Devise a heater coil with no uncompensated length

6.2 POWER CONTROLLER

A block diagram of the power control is shown in Fig. 11. The power control will include standard Space Station components, including an embedded data processor (EDP) a multiplexer-demultiplexer (MDM), and a network interface

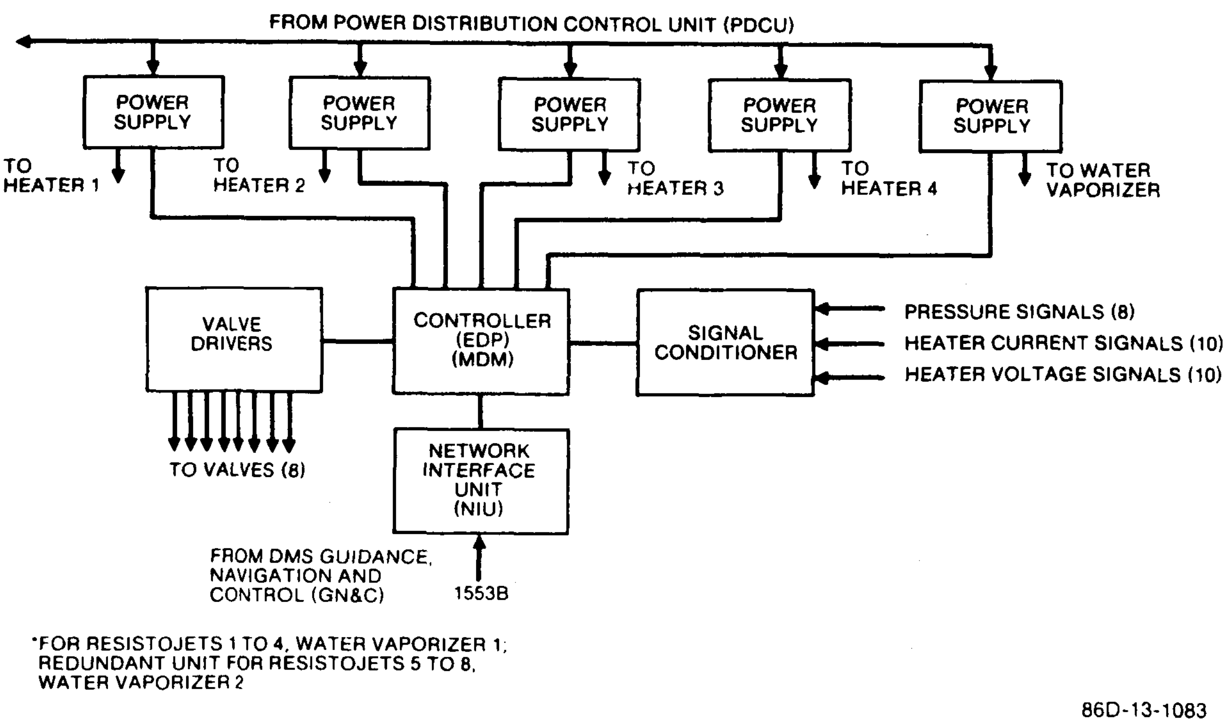

Figure 11. Resistojet Power Control Block Diagram

unit (NIU). Four resistojets and a water vaporizer share a common controller, which eliminates the need for separate interfaces to the data management system (DMS). The second set of four resistojets and water vaporizer has a duplicate controller to provide redundancy.

Power to the resistojet heaters is obtained from individual power supplies that transform the standard 208-Vac, 20-kHz power source from the power distribution control unit (PDCU) to approximately 22.4/16 Vac to provide 500/250 W to each resistojet. A Space Station standard embedded data processor is used to decode the on/off and power level commands for the resistojets from the guidance, navigation, and control (GN&C) system by way of a standard network interface unit that accesses the DMS. The EDP has two separate wires to each power supply/switch to turn on either full or intermediate power as commanded by the GN&C system.

A signal conditioner is used to measure and convert the analog heater voltage and current as well as inlet thruster pressure from each resistojet in the cluster of four to digital format so that it can be read by the EDP and forwarded to Space Station telemetry over the DMS via the NIU. The EDP also will provide health monitoring for the subsystem.

A shown in Fig. 11, drivers for the run valves for the resistojets are included in the power controller. Additional study of the overall propulsion system, including the 25-lbf GO_2/GH_2 thrusters and the resistojets, may indicate that operation of the valves is best accomplished by the main propulsion computer. The function of the power controller would then be limited to supplying power to the resistojets as demanded by the main computer. The power supplies for the resistojets must be close-coupled, within a few feet, to the resistojets to minimize power loss.

The features of the power control are summarized in Table 11.

The power control for each set of four resistojets and one water vaporizer will be packaged as an integral unit (Fig. 12). The overall dimensions of each of the two power controls are 4.5 by 6 by 18 in. The estimated weight of each of the two power controls is 15 lb.

6.3 WATER VAPORIZER

Potential methods of supplying steam to the inlet of the resistojet include:

1. Installation of an on-line water vaporizer at the inlet of each resistojet

2. Provision of one on-line water vaporizer for each set of four resistojets

3. Heating a tank of high-pressure water (off-line, while the resistojets are not in operation) and flashing the water through an orifice to steam at low pressure.

TABLE 11

CONTROLLER

- **INCLUDES STANDARD SPACE STATION COMPONENTS**
  - EMBEDDED DATA PROCESSOR (EDP)
  - NETWORK INTERFACE UNIT (NIU)
  - MULTIPLEXER-DEMULTIPLEXER (MDM)
- **FOUR RESISTOJETS AND ONE WATER VAPORIZER SHARE COMMON CONTROLLER**
  - ELIMINATES NEED FOR SEPARATE INTERFACES TO GN&C
- **INDIVIDUAL POWER SUPPLY FOR EACH HEATER**
  - TRANSFORMS 208 Vac, 20 kHz FROM PDCU TO ~20/16 Vac TO PROVIDE 500/250 W
- **EDP DECODES ON/OFF AND POWER LEVEL COMMANDS FROM GN&C VIA THE NIU**
- **SIGNAL CONDITIONER CONVERTS ANALOG CURRENT, VOLTAGE, PRESSURE SIGNALS TO DIGITAL FORMAT FOR EDP WHICH SENDS DATA TO TELEMETRY OVER THE DMS VIA THE NIU**
- **ENVELOPE ~4.5 in. x 6 in. x 18 in. FOR EACH OF TWO CONTROLLERS**
- **WEIGHT ~15 lb FOR EACH OF TWO CONTROLLERS**

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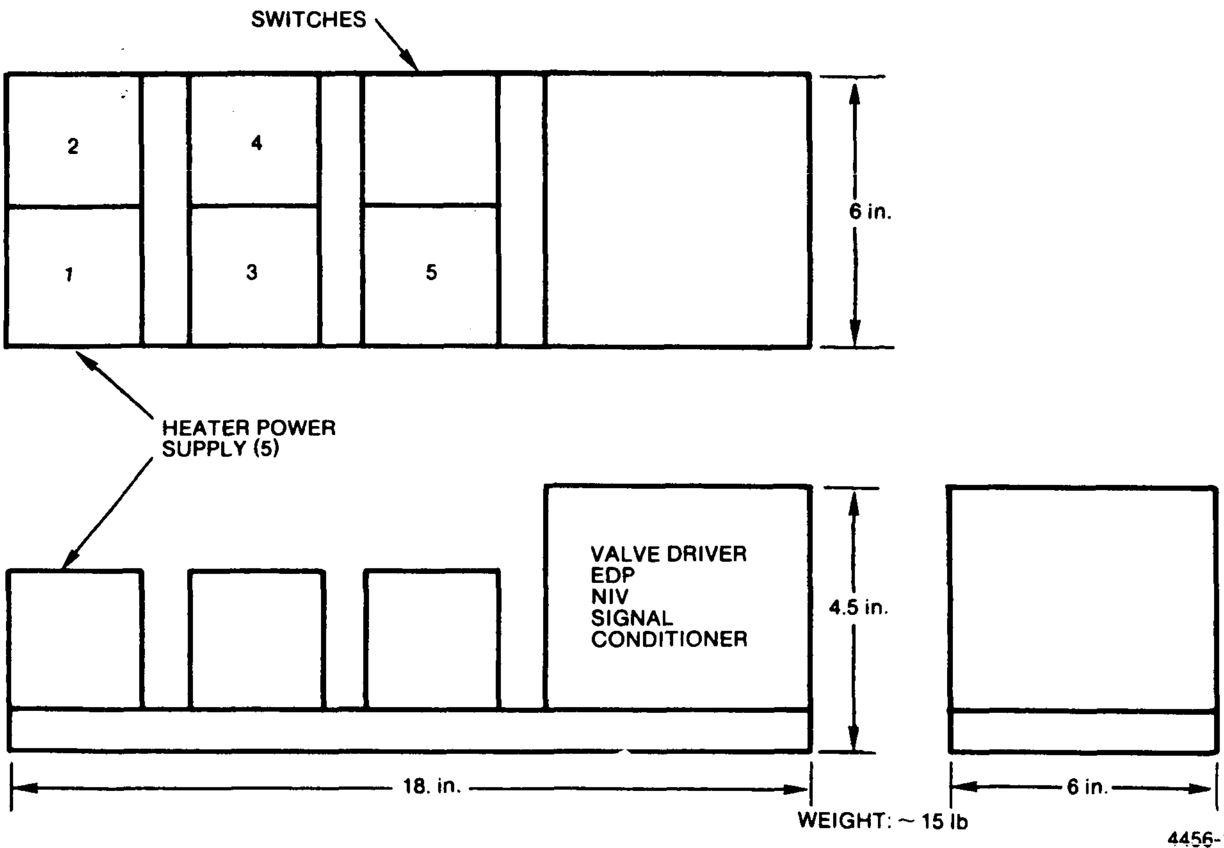

Figure 12. Controller Packaging

The advantages and disadvantages of each method are summarized in Table 12. The first method results in minimum heat loss downstream of the vaporizer and provides the same redundancy as the resistojet. However, all of the waste fluids must pass through the water vaporizer (with power off for all but water), which imposes additional materials compatibility requirements on the vaporizer. In addition, the total system parts count is increased.

In the second method, a water vaporizer is close-coupled to a set of four resistojets. Only water/steam fluids pass through the vaporizer. The steam can be directed to any resistojet through the manifolding. This method requires insulation of the manifold and will result in more power loss than the first method. However, the second method reduces the parts count and reduces material compatibility requirements for the vaporizer.

The third method is commonly used to supply steam to steam ejectors. Heating the high-pressure water can be accomplished at low power over a long time when the resistojets are not operating. Thus, the power level is minimized. Or conversely, the maximum number of resistojets can be operated simultaneously for a given maximum power level. The disadvantages of this method are the

TABLE 12

POTENTIAL WATER VAPORIZATION METHODS

METHOD	ADVANTAGES	DISADVANTAGES
1. ON-LINE VAPORIZER AT INLET OF EACH RESISTOJET	MINIMUM HEAT LOSS DOWNSTREAM OF VAPORIZER	ALL WASTE GAS FLOWS THROUGH VAPORIZER, INCREASING COMPATIBIL- ITY REQUIREMENTS INCREASES TOTAL PARTS COUNT
2. ONE ON-LINE VAPO- RIZER FOR EACH SET OF FOUR RESISTOJETS	ONLY WATER/STEAM FLOWS THROUGH VAPORIZER	STEPPED HEATED POWER REQUIRED IF MORE THAN ONE RESISTOJET OPER- ATES SIMULTANEOUSLY INSULATED STEAM LINE
3. HEATED HIGH PRES- SURE WATER TANK, FLASH TO STEAM	HEAT CAN BE APPLIED AT LOW POWER OVER LONG TIME WHILE RESISTOJETS ARE NOT OPERATING	HEAT LOSS INSULATED TANK AND LONG LINE

- **NUMBER 2 METHOD SELECTED**

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additional heat loss from the heated insulated tanks and through the long insulated lines between the tanks and the resistojets. In addition, appreciable inductance power loss will occur if the water tanks are located upstream of the stinger and the water vaporizer power supply is located with the resistojet power supply adjacent to the resistojets.

A two-set-point power control, which is nearly identical to that required for the resistojet heaters, can be used for the water vaporizer for the second method. One set point would be used if one resistojet were operated; the other set point with two times the power, would be used if two resistojets were operated. The power to vaporize the water is approximately the same as that required for a 500-W resistojet:

$$q = \dot{W}\ \Delta h$$

The enthalpy change (Δh) of water at 70°F, 40 psia to superheated steam at 300°F, 40 psia is approximately 1147 Btu/lb. The power required for a water flow of 1.31 lb/h for one resistojet and a thermal loss of 10% is

$$\text{Power} = \frac{(1.31)(1147)}{(0.9)} \left(\frac{0.293\ \text{W}}{\text{Btu/h}}\right) = 489\ \text{W}$$

Thus, one operating 500-W resistojet plus vaporizer requires nearly 1000 W. Two operating resistojets plus vaporizer will require nearly 2000 W. If the maximum power is limited to 2 kW, only two resistojets operating on steam can be operated simultaneously (Table 13).

The second method, with one water vaporizer supplying any one or two of a set of four resistojets, is tentatively selected for the resistojet assembly because of the low parts count, reduced materials compatibility requirements, and nearly identical power control as required for the resistojet heaters.

TABLE 13

WATER VAPORIZER

- **POWER REQUIRED TO CONVERT WATER AT 70°F, 40 psia TO STEAM AT 300°F, 40 psia = 490 W FOR 1-500 W RESISTOJET**
- **ONE RESISTOJET OPERATING ON WATER REQUIRES ~1 kW**
- **TWO RESISTOJETS CAN OPERATE SIMULTANEOUSLY IF MAXIMUM ALLOWABLE POWER IS 2 kW**
- **TWO SET POINT HEATER POWER (LIKE RESISTOJETS)**

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The water vaporizer design is similar to the design of the resistojet heater, i.e., a length of heater tube is coiled around a fluid heat exchanger. The vaporizer size is driven by the maximum allowable power flux from the surface of the heater. The high convective heat transfer coefficient on the fluid side (for the sensible heat rise of the water, boiling, and superheat), results in low fluid surface requirements. The length of heater wire is approximately 20 in. for a power flux from the heater sheath of 100 W/in.^{2}. At a 0.9-in. pitch diameter, seven heater turns are required. The fluid flow channel is helical with a cross section of approximately 0.10 by 0.080 in. The vaporizer design is illustrated in Fig. 13. The overall envelope is 3-in. diameter by 4 in. long. The estimated weight is 4 lb.

6.4 LATCH VALVE

Latch valves are required to minimize power drain because of the long operating times for the resistojet. No power is required after actuation to either the open or closed position.

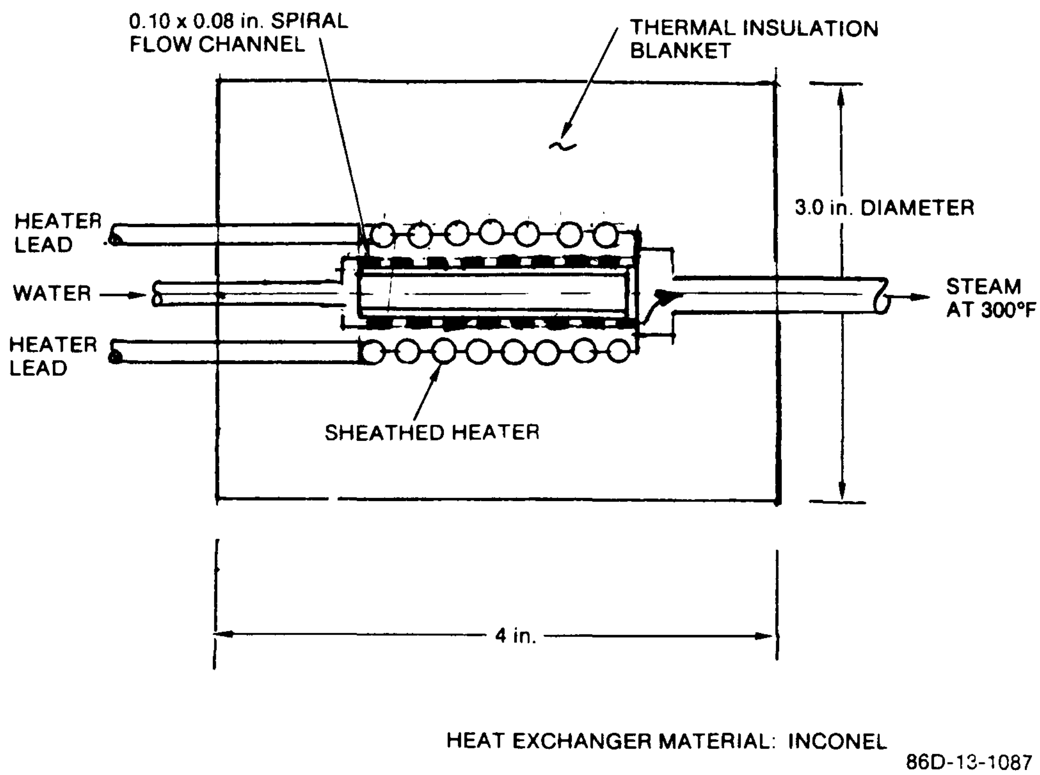

Figure 13. Water Vaporizer Concept

A candidate latch valve is the Wright Components, Inc., P/N 15875 valve (Fig. 14). This valve has been used on most resistojet thrusters on flight programs. Valve characteristics are summarized in Table 14. The valve contains two solenoids, one for opening and one for closing. Latching is accomplished by overcenter stroking a Belleville spring washer with either solenoid. The selection of the valve seat material is contingent upon the temperature range and gas composition of the waste gas. Teflon and ethylene propylene and kalrez are leading candidates for the valve seat material based on the preliminary requirements.

6.5 PRESSURE REGULATOR

A pressure regulator is required that is capable of an operating time well over the 10,000-h operating life of a single resistojet. In addition, the regulator must operate with a variety of reducing or oxidizing gases. The inlet pressure will vary from 500 psig to approximately 75 psia. The outlet pressure must be maintained at approximately 40 ± 3 psia over the range of inlet pressures for one to four resistojets operating simultaneously.

The Futurecraft Corporation P/N 400332 pressure regulator is a candidate. This pressure regulator (Fig. 15) is a single-stage, spring-loaded device. The weight is 0.53 lb. Pressure regulator parameters are summarized in Table 15.

6.6 MANIFOLD AND TUBING

The tubes along the 60-ft-long stinger, which supply the waste fluids to the thrusters, are included in the resistojet assembly if the interface between the waste gas storage system and the resistojet assembly is selected immediately downstream from the shut-off valves in the storage subsystem. The calculated pressure loss through the tubes along the boom is summarized in Table 16. With four resistojets operating with the nominal mixed-gas composition at a minimum tank pressure of 75 psia, the pressure loss is 0.7 psi for a single 0.25-in. OD tube. The pressure loss for each sharp right angle bend is calculated to be a maximum of 0.01 psi upstream of the pressure regulator and 0.02 psi downstream from the pressure regulator. The pressure losses are acceptably low. A tube diameter of 0.25 in. is satisfactory for the lines along the stinger and the manifold downstream of the pressure regulator.

6.7 WEIGHT SUMMARY

A weight summary for the resistojet assembly is presented in Table 17. The weights include all fluid components downstream from the shut-off valves in the storage subsystem to the thrusters, including fluid tubing in the boom; power controls, cables, and wiring; and structure and shielding. The total dry weight is approximately 167 lb.

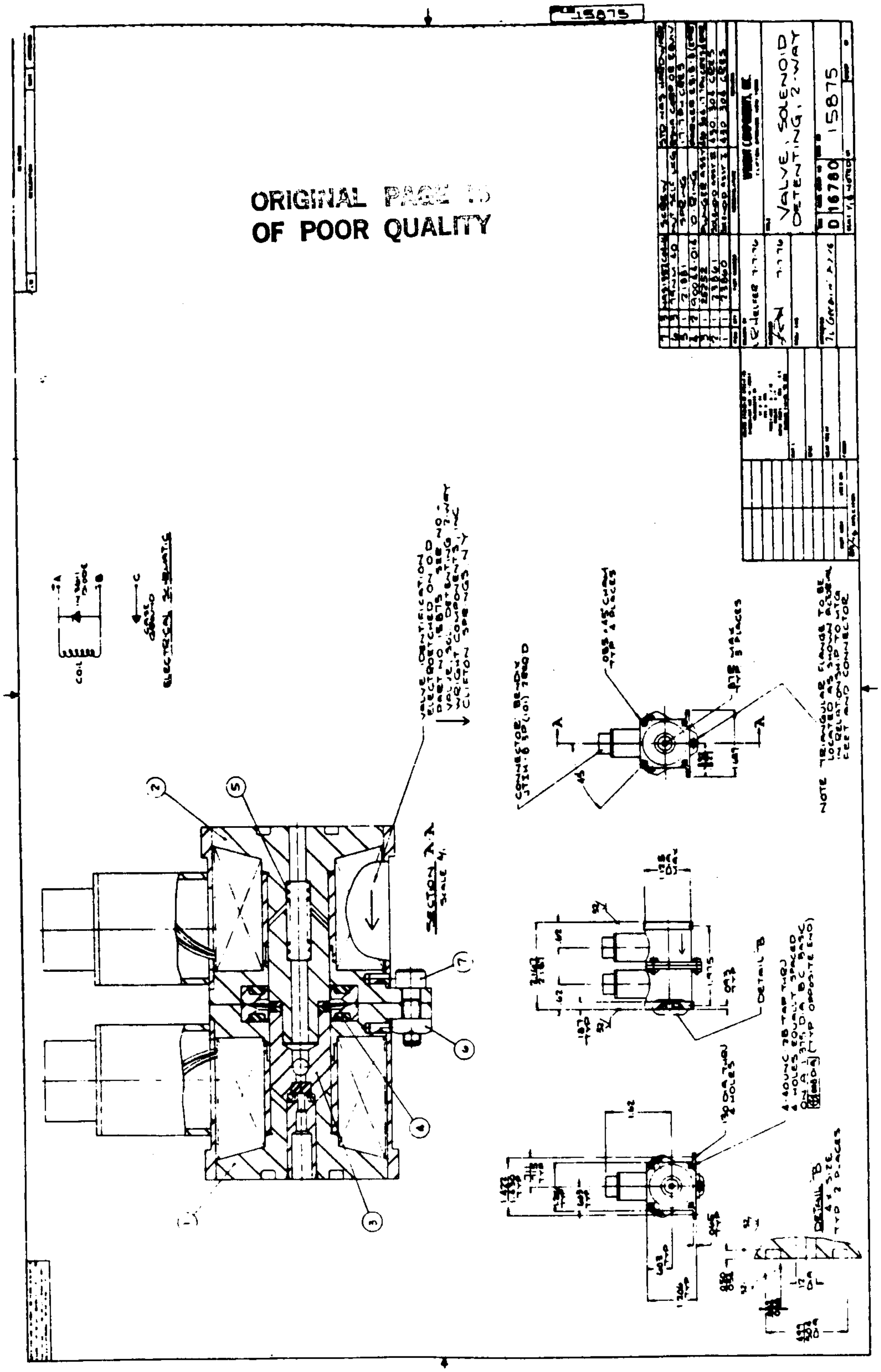

Figure 14. Candidate Latch Valve

TABLE 14

LATCH VALVE

- **LATCHING VALVES ARE REQUIRED TO MINIMIZE POWER DRAIN BECAUSE OF LONG ON-TIME**
- **CANDIDATE VALVE IS WRIGHT COMPONENTS P/N 15875**
    - USED ON MOST RESISTOJET THRUSTERS ON FLIGHT PROGRAMS
- **NO POWER DRAIN IN EITHER OPEN OR CLOSED POSITION OBTAINED BY OVER-CENTER STROKING OF BELLVILLE SPRING WASHER WITH TWO SOLENOIDS, ONE TO OPEN AND ONE TO CLOSE**
- **INLET DIAMETER = 0.126 in.**
- **EQUIVALENT DIAMETER = 0.045 in.**
- **C_D = 0.65**
- **ΔP = 4.2 psi FOR TWO VALVES IN SERIES FOR MIXED GAS FLOW**

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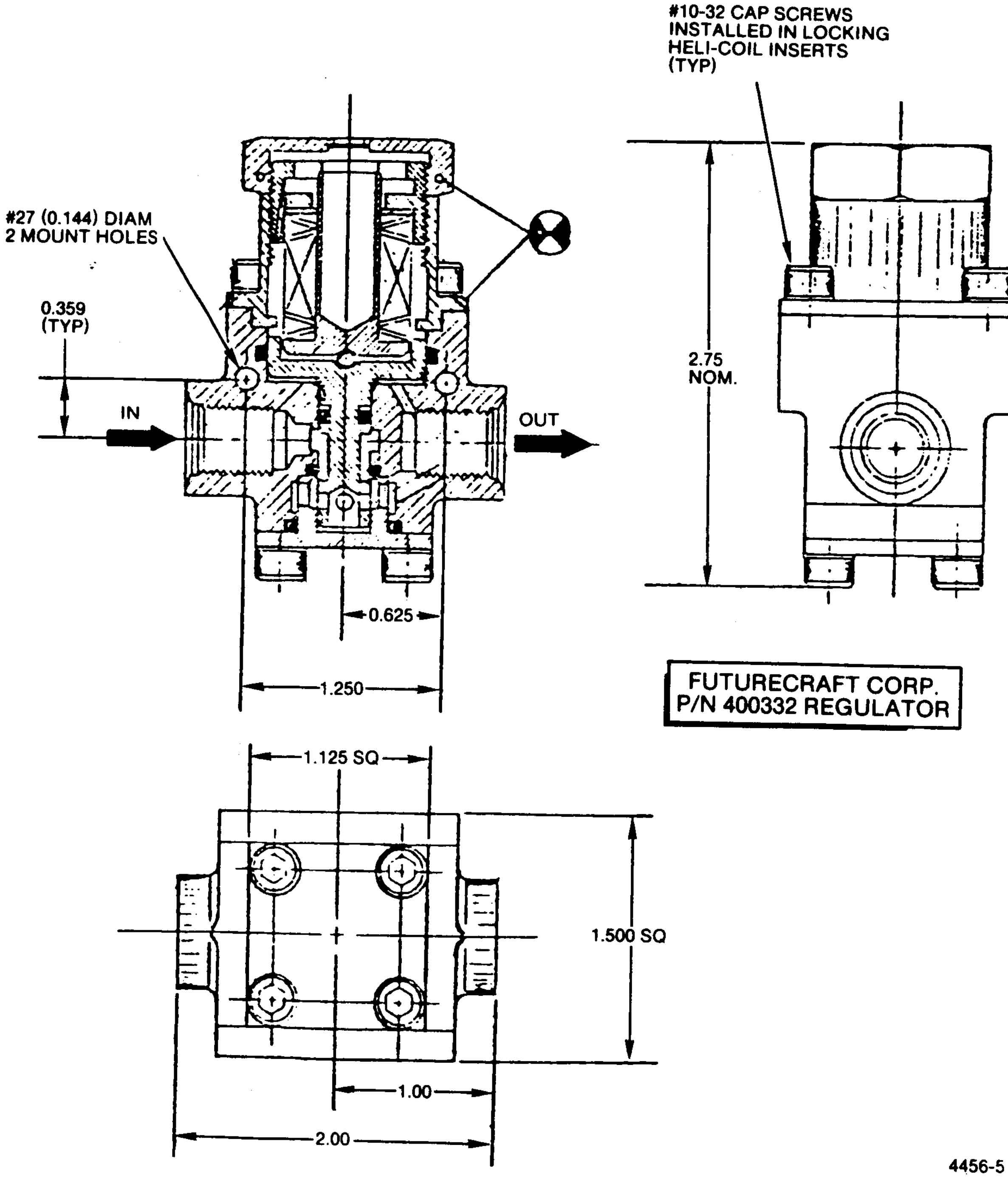

Figure 15. Regulator Adjustable Precision High Flow Capacity

TABLE 15

PRESSURE REGULATOR

• **INLET PRESSURE (psia)**	**500 TO 75**
• **OUTLET PRESSURE (psia)**	**40 ± 3**
• **TYPE**	**SINGLE STAGE, SPRING LOADED**
• **EQUIVALENT DIAMETER OF ORIFICE AT FULL OPEN (in.)**	**~0.05**
• **CANDIDATE VALVE**	**FUTURECRAFT CORP. PN 400332**
• **WEIGHT (lb)**	**0.53**

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TABLE 16

MANIFOLD AND TUBING

- **TUBES ALONG 60 ft LONG BOOM**
  - $\Delta P \simeq 0.7$ psi FRICTION LOSS
  - $\Delta P \simeq 0.01$ psi PER SHARP RIGHT ANGLE BEND
    - PRESSURE REGULATOR DOWNSTREAM OF TUBE (P = 75 psia)
- **MANIFOLD DOWNSTREAM OF REGULATOR**
  - $\Delta P = 0.02$ psi PER SHARP RIGHT ANGLE BEND
    - P = 40 psia
- **FOR FOUR RESISTOJETS OPERATING WITH MIXED GAS 0.25 in. TUBE OUTSIDE DIAMETER, 0.015 in. WALL THICKNESS**

86D-13-1092

TABLE 17

RESISTOJET PROPULSION MODULE WEIGHT SUMMARY

COMPONENT	QUANTITY	UNIT WEIGHT (lb)	TOTAL WEIGHT (lb)
RESISTOJET	8	8.0	64.0
CONTROLLER	2	15.0	30.0
LATCH VALVE	16	0.4	6.4
PRESSURE TRANSDUCER	2	0.3	0.6
CHECK VALVE	6	0.2	1.2
PRESSURE REGULATOR	4	0.5	2.0
WATER VAPORIZER	2	4.0	8.0
FILTER	6	0.1	0.6
DISCONNECTS	8	0.4	3.2
MANIFOLDING AND TUBING*	2	9.2	18.4
CABLES AND WIRING*	2	5.0	10.0
STRUCTURE	1	20.0	20.0
THERMAL SHIELDING	1	3.0	3.0
TOTAL			167.4

*INCLUDING TUBING AND WIRING ALONG BOOM

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7.0 INTERFACE DEFINITION

The interfaces for the resistojet assembly include structural, fluid, power, control signals, and performance (health monitoring) data.

The structural interface consists of the mechanical attachment of the resistojet assembly to the stinger. The attachment must allow in-orbit mounting of both resistojet subassemblies, with each subassembly as defined in Section 4.0. In addition, the attachment must allow removal of either one of the subassemblies and replacement with the ORU, if necessary.

The fluid interface consists of the fluid disconnects at the upstream end of the stinger near the shut-off valves in the waste fluids storage subassembly. There are two fluid disconnects for each of the three types of fluids: reducing gas, water, and oxidizing gas.

The interface with the power distribution control unit (PDCU) consists of one shielded coaxial cable connection to each of the two power controllers. The power interface is located at the upstream end of the stinger, near the fluid interface.

The interface with the control and health monitoring signals consists of one 1553B cable connection for each subassembly. The cable connections are located at the upstream end of the stinger near the fluid interface.

8.0 TEST AND VERIFICATION

Test and verification of the hardware, software, and support equipment for the resistojet assembly involve (1) development, qualification, and acceptance tests at the component level and with the subassembly, and (2) major ground test, prelaunch preparation, and in-orbit verification of the assembly. Two identical subassemblies, one of which is redundant, comprise the resistojet assembly.

The philosophy for cost-effective test and verification is based upon

- The protoflight concept
- A combination of test, analysis demonstration, and inspection for verification
- Minimizing dedicated test hardware

With the protoflight concept, as much as possible of the hardware after qualification testing is refurbished, re-acceptance tested, and incorporated into the flight resistojet assembly. The level of qualification testing for the protoflight concept is specified in MIL-STD 1540B.

A test and verification flow chart from component test through operational checkout in orbit is shown in Fig. 16. The type of test at each stage of test and verification is indicated. Typical tests are listed in Table 18. In orbit testing includes verifying the integrity of fluid and electrical connections, activation tests, and final readiness verification.

The test and verification is integrated into the schedule shown in Fig. 17.

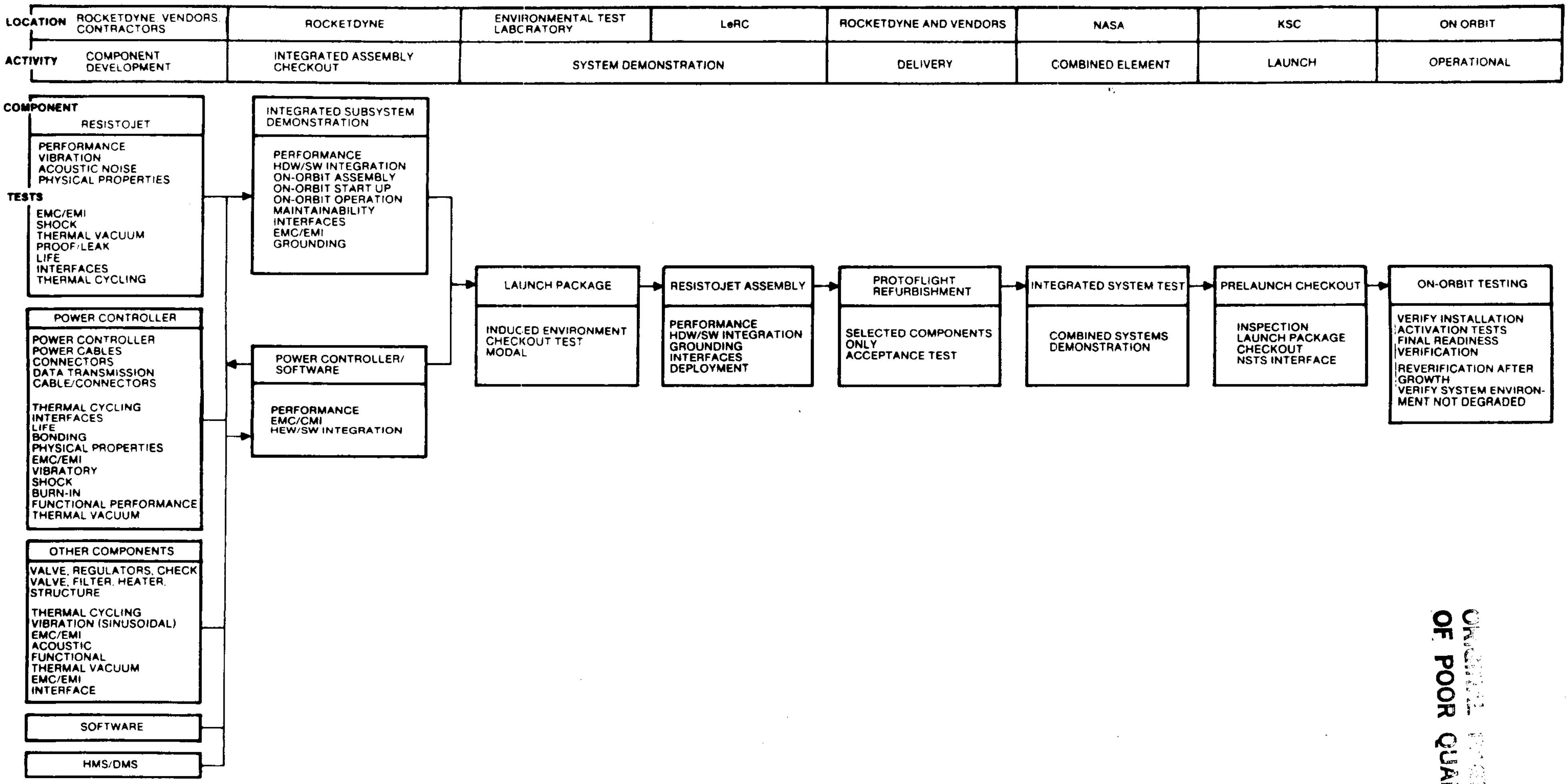

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Figure 16. Resistojet Assembly Test and Verification Flow

TABLE 18

TYPICAL ORU TEST REQUIREMENTS

TEST REQUIREMENT	TEST CATEGORY		
	QUAL	ACCEPTANCE	ON ORBIT
FUNCTIONAL TEST	X	X	X
PERFORMANCE	X	X	X
INTERFACES	X		X
PRESSURE	X	X	
FLIGHT VIBRATION *	X		
THERMAL CYCLING	X		
THERMAL VACUUM	X	X	X
ACCELERATION	X		
ACOUSTIC*	X		
FLIGHT SHOCK	X		
LEAK	X	X	
EMC/EMI	X		
LIFE	X		
TRANSPORTABILITY	X		

* BOTH NOT REQUIRED

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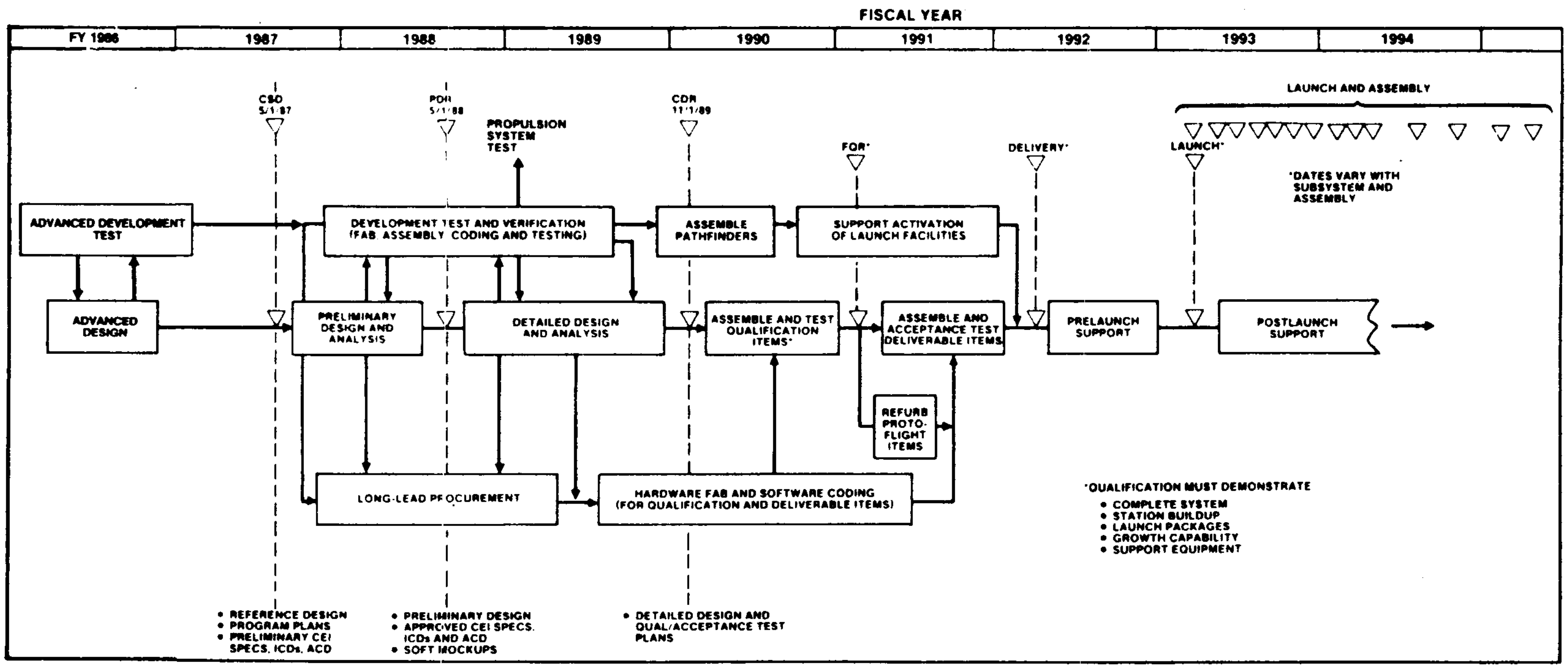

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Figure 17. Phase C/D Program Plan Logic and Schedule

9.0 DDT&E AND FLIGHT UNIT COST

A preliminary cost for the design, development, test, evaluation, qualification, and flight hardware of the resistojet assembly was prepared. Ground rules for the cost estimates are listed in Table 19. The flight hardware consists of three identical subassemblies. Two subassemblies, one of which is redundant, comprise the resistojet assembly installed at the end of the stinger. The third subassembly serves as the orbital replacement unit (ORU).

The data bus interface unit, embedded data processor, multiplexer-demultiplexer, and valve drivers are considered to be government-furnished or WP-02 contractor-furnished equipment. Consequently, design, development test, and hardware cost for these components are not included.

Cost estimates do not include overall program management for integration into the overall propulsion system. This effort is assumed to be the function of the WP-02 contractor.

A summary of the costs is presented in Table 20. Costs are expressed in constant FY 1987 dollars. The costs include all applicable overheads and factors. No fee has been included in the estimate. The total cost is estimated to be $16 million.

A cost breakdown by component is presented in Table 21.

TABLE 19

GROUND RULES FOR ROM COST ESTIMATE OF
RESISTOJET PROPULSION MODULE

- **DDT&E, QUALIFICATION, AND FLIGHT HARDWARE**
- **DATA BUS INTERFACE UNIT, EDP, MDM, GN&C THRUSTER VALVE DRIVER ARE GFE (REFERENCE: PROPULSION ASSEMBLY ELEMENT BCD, OCTOBER 9, 1986)**
- **PROGRAM MANAGEMENT IS INCLUDED IN OVERALL SPACE STATION PROPULSION SYSTEM EFFORT**
- **INTEGRATION WITH SPACE STATION IS RESPONSIBILITY OF WP-02 CONTRACTOR**
- **FY 1987 DOLLARS WITHOUT FEE**

86D-13-1216

TABLE 20

ROM COST OF DDT&E AND FLIGHT RESISTOJET
PROPULSION MODULE

CATEGORY	COST (K$)		
	COMPONENT DEVELOPMENT, TEST BED AND PROTOTYPE MODULES	QUALIFICATION MODULE	FLIGHT MODULE
LABOR	4578	939	295
HARDWARE	1320	1061	5242
SUPPLIER NON-RECURRING	1934	744	—
TOTAL	7832	2744	5537

TOTAL 16,113

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TABLE 21

OVERALL PROGRAM SUMMARY
(Sheet 1 of 4)

SPACE STATION PHASE C/D PROPULSION SYSTEM HARDWARE
RESISTOJET SYSTEM - 3 LEG SYSTEM
10/20/86

Rocketdyne Division
Rockwell International

ITEM NO.	PART NAME	DESCRIPTION	WEIGHT LBS/UNIT	FY87 AVG UNIT COST	FLIGHT HARDWARE PER ASSEMBLY QTY	WEIGHT (LBS)	COST ($K)	TOTAL FLIGHT HARDWARE 3 ASSYS QTY	WEIGHT (LBS)	COST ($K)	BASIS AVG UNIT COST	BASE YEAR	AVG UNIT COST 1987
1	WATER VAPORIZER	ELECTRICALLY HEATED, ON-LINE UNIT	4.00	$15.8	1	4.0	$16	3	12.0	$48	15.00	1986	$15.8
2	THRUSTER LATCH VALVE	2 SOLENOIDS, 1 VALVE SEAT	0.40	10.6	8	3.2	84	24	9.6	253	10.00	1986	10.6
3	CHECK VALVE	COMMON UNIT FOR ALL FLUIDS	0.20	2.1	3	0.6	6	9	1.8	19	2.00	1986	2.1
4	REGULATOR	SINGLE STAGE, SPRING LOADED	0.50	10.6	2	1.0	21	6	3.0	63	10.00	1986	10.6
5	FILTER	HIGH FILTRATION, LOW CAPACITY	0.10	2.1	4	0.4	8	12	1.2	25	2.00	1986	2.1
6	DISCONNECT	COMMON TO OTHER STATION DISCONNECTS	0.40	13.9	4	1.6	56	12	4.8	167	12.00	1984	13.9
7	CABLES & WIRE	PER FOOT, 60 FEET LONG	0.10	0.2	20	2.0	5	60	6.0	14	0.20	1984	0.2
8	STRUCTURE & SHIELDING	INCLUDES 3.0 LBS OF SHIELDING	13.00	33.4	1	13.0	33	3	39.0	100	28.73	1984	33.4
9	MANIFOLDING & TUBING		9.20	23.6	1	9.2	24	3	27.6	71	20.33	1984	23.6
10	THRUSTERS	.08 LBF; 200 SEC AVG ISP	8.00	211.2	4	32.0	845	12	96.0	2,535	200.00	1986	211.2
11	PRESSURE TRANSDUCERS	STRAIN GAGE; REMOTE SENSING	0.30	5.8	8	2.4	46	24	7.2	139	5.00	1984	5.8
12	CONTROL AND POWER UNIT	4 POWER SUPS, 1 VAPOR., 1 SIGNAL COND.	15.00	180.0	1	15.0	180	3	45.0	540	180.00	1987	180.0
	SUBTOTAL COST-P.O. 1.00	NOTE: TOTAL QUANTITY COUNTS DO NOT INCLUDE FUEL LINE NOR WIRING			37	84.4	$1,325	111	253.2	$3,975			
	SUBTOTAL COST-R/D. 1.22						1,616			4,849			
	ROCKETDYNE ASSEMBLY				1		131	3		393	124	1986	131.0
	TOTAL HARDWARE COST						$1,747			$5,242			

PROGRAM SUMMARY -FY87 $K -NO FEE INCLUDED	R/D ENGR & TEST LABOR HOURS	DOLLARS	SUPPLIER P.O.	NON-REC COST	HARDWARE	OTHER	TOTAL
TEST BED & PROTO MODULE	77,798	$4,548	$1,585	$1,934	$1,320	$30	$7,832
QUALIFICATION	15,692	917	610	744	1,061	22	2,744
FLIGHT HARDWARE	5,040	295			5,242		5,536
TOTAL PROGRAM COST	98,530	$5,760	$2,195	$2,678	$7,623	$52	$16,113

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TABLE 21

OVERALL PROGRAM SUMMARY
(Sheet 2 of 4)

SPACE STATION PHASE C/D PROPULSION SYSTEM HARDWARE
RESISTOJET SYSTEM - 3 LEG SYSTEM
10/20/86

Rocketdyne Division
Rockwell International

ITEM NO.	PART NAME	DESCRIPTION	WEIGHT LBS/UNIT	FY87 AVG UNIT COST	TOTAL FLIGHT HARDWARE 3 ASSYS QTY	WEIGHT (LBS)	COST ($K)	BASIS OF ESTIMATE	TOTAL DEV HDWE REQUIREMENTS QTY	COST ($M)	NON-RECURRING TOTAL $K	TOTAL PROGRAM COST
1	WATER VAPORIZER	ELECTRICALLY HEATED, ON-LINE UNIT	4.00	$15.8	3	12.0	$48	ESTIMATE	6	$95.0	$163	$337
2	THRUSTER LATCH VALVE	2 SOLENOIDS, 1 VALVE SEAT	0.40	10.6	24	9.6	253	WRIGHT	12	126.7	313	777
3	CHECK VALVE	COMMON UNIT FOR ALL FLUIDS	0.20	2.1	9	1.8	19	PEACEKEEPER	7	14.8	192	233
4	REGULATOR	SINGLE STAGE, SPRING LOADED	0.50	10.6	6	3.0	63	MINUTEMAN	6	63.4	349	504
5	FILTER	HIGH FILTRATION, LOW CAPACITY	0.10	2.1	12	1.2	25	SHUTTLE DERIVED	9	19.0	192	246
6	DISCONNECT	COMMON TO OTHER STATION DISCONNECTS	0.40	13.9	12	4.8	167	SHUTTLE	8	111.5	153	492
7	CABLES & WIRE	PER FOOT, 60 FEET LONG	0.10	0.2	60	6.0	14	SHUTTLE	40	9.3	153	181
8	STRUCTURE & SHIELDING	INCLUDES 3.0 LBS OF SHIELDING	13.00	33.4	3	39.0	100	ESTIMATE	3	100.1	153	397
9	MANIFOLDING & TUBING		9.20	23.6	3	27.6	71	ESTIMATE	2	47.2	0	144
10	THRUSTERS	.08 LBF; 200 SEC AVG ISP	8.00	211.2	12	96.0	2,535	TECHNION	4	844.8	1,220	5,343
11	PRESSURE TRANSDUCERS	STRAIN GAGE; REMOTE SENSING	0.30	5.8	24	7.2	139	ESTIMATE	10	58.1	61	302
12	CONTROL AND POWER UNIT	4 POWER SUPS, 1 VAPOR., 1 SIGNAL COND.	15.00	180.0	3	45.0	540	ESTIMATE	2	360.0	3,500	4,598
	SUBTOTAL COST-P.O. 1.00	NOTE: TOTAL QUANTITY COUNTS DO NOT INCLUDE FUEL LINE NOR WIRING			111	253.2	$3,975		69	$1,850		
	SUBTOTAL COST-R/D. 1.22						4,849			$2,257	$6,448	$13,554
	ROCKETDYNE ASSEMBLY				3		393		3	124	1,695	2,212
	TOTAL HARDWARE COST						$5,242			$2,381	$8,143	$15,766

PROGRAM SUMMARY
-FY87 $K
-NO FEE INCLUDED

	R/D ENGR & TEST LABOR HOURS	DOLLARS	SUPPLIER P.O.	NON-REC COST	HARDWARE	OTHER	TOTAL
TEST BED & PROTO MODULE	77,798	$4,548	$1,585	$1,934	$1,320	$30	$7,832
QUALIFICATION	15,692	917	610	744	1,061	22	2,744
FLIGHT HARDWARE	5,040	295			5,242		5,536
TOTAL PROGRAM COST	98,530	$5,760	$2,195	$2,678	$7,623	$52	$16,113

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TABLE 21

OVERALL PROGRAM SUMMARY
(Sheet 3 of 4)

SPACE STATION PHASE C/D PROPULS RESISTOJET SYSTEM - 3 LEG SYSTE 10/20/86

ITEM NO.	PART NAME	BASIS OF ESTIMATE	FPT TEST HARDWARE REQUIREMENTS QTY	FPT TEST HARDWARE REQUIREMENTS COST ($M)	QUAL TEST HARDWARE REQUIREMENTS QTY	QUAL TEST HARDWARE REQUIREMENTS COST ($M)	TOTAL DEV HDWE REQUIREMENTS QTY	TOTAL DEV HDWE REQUIREMENTS COST ($M)	DDT&E NON-RECURING SUPPLIER P.O. $K	DDT&E NON-RECURING SUPPLIER $K 1.22	DDT&E NON-RECURING R/D LABOR HOURS	DDT&E NON-RECURING R/D LABOR $K $58.46	DDT&E NON-RECURING TOTAL $K
1	WATER VAPORIZER	ESTIMATE	4	$63.4	2	$31.7	6	$95.0	75	$92	500	$29	$121
2	THRUSTER LATCH VALVE	WRIGHT	8	84.5	4	42.2	12	126.7	120	146	920	54	200
3	CHECK VALVE	PEACEKEEPER	6	12.7	1	2.1	7	14.8	75	92	460	27	118
4	REGULATOR	MINUTEMAN	4	42.2	2	21.1	6	63.4	150	183	920	54	237
5	FILTER	SHUTTLE DERIVED	6	12.7	3	6.3	9	19.0	75	92	460	27	118
6	DISCONNECT	SHUTTLE	6	83.6	2	27.9	8	111.5	100	122		0	122
7	CABLES & WIRE	SHUTTLE	20	4.6	20	4.6	40	9.3	100	122		0	122
8	STRUCTURE & SHIELDING	ESTIMATE	2	66.7	1	33.4	3	100.1	100	122		0	122
9	MANIFOLDING & TUBING	ESTIMATE	1	23.6	1	23.6	2	47.2		0		0	0
10	THRUSTERS	TECHNION	2	422.4	2	422.4	4	844.8	750	915		0	915
11	PRESSURE TRANSDUCERS	ESTIMATE	6	34.8	4	23.2	10	58.1	40	49		0	49
12	CONTROL AND POWER UNIT	ESTIMATE	1	180.0	1	180.0	2	360.0		0	54,738	3,200	3,200
	SUBTOTAL COST-P.O. 1.00		46	$1,031	23	$819	69	$1,850	$1,585				
	SUBTOTAL COST-R/D. 1.22			$1,258		$999		$2,257		$1,934	57,998	$3,391	$5,324
	ROCKETDYNE ASSEMBLY		2	62	1	62	3	124			19,800	1,158	1,158
	TOTAL HARDWARE COST			$1,320		$1,061		$2,381		$1,934	77,798	$4,548	$6,482

4456-6-3

TABLE 21

OVERALL PROGRAM SUMMARY
(Sheet 4 of 4)

SPACE STATION PHASE C/D PROPULS RESISTOJET SYSTEM - 3 LEG SYSTE 10/20/86		QUALIFICATION NON-RECURRING					TOTAL NON-RECURRING					TOTAL PROGRAM COST
ITEM NO.	PART NAME	SUPPLIER P.O. $K	SUPPLIER $K 1.22	R/D LABOR HOURS	R/D LABOR $K $58.46	TOTAL $K	SUPPLIER P.O. $K	SUPPLIER $K 1.22	R/D LABOR HOURS	R/D LABOR $K $58.46	TOTAL $K	
1	WATER VAPORIZER	25	$31	200	$12	$42	$100	$122	700	$41	$163	$337
2	THRUSTER LATCH VALVE	75	92	360	21	113	195	238	1,280	75	313	777
3	CHECK VALVE	50	61	220	13	74	125	153	680	40	192	233
4	REGULATOR	75	92	360	21	113	225	275	1,280	75	349	504
5	FILTER	50	61	220	13	74	125	153	680	40	192	246
							125	153	0	0	153	492
6	DISCONNECT	25	31		0	31	125	153	0	0	153	181
7	CABLES & WIRE	25	31		0	31	125	153	0	0	153	397
8	STRUCTURE & SHIELDING	25	31		0	31	0	0	0	0	0	144
9	MANIFOLDING & TUBING		0		0	0						
							1,000	1,220	0	0	1,220	5,343
10	THRUSTERS	250	305		0	305	50	61	0	0	61	302
11	PRESSURE TRANSDUCERS	10	12		0	12	0	0	59,870	3,500	3,500	4,598
12	CONTROL AND POWER UNIT		0	5,132	300	300						
	SUBTOTAL COST-P.O. 1.00	$610	$744	6,492	$380	$1,124	$2,195	$2,678	64,490	$3,770	$6,448	$13,554
	SUBTOTAL COST-R/D. 1.22			9,200	538	538			29,000	1,695	1,695	2,212
	ROCKETDYNE ASSEMBLY		------	------	------	------		------	------	------	------	--------
	TOTAL HARDWARE COST		$744	15,692	$917	$1,662		$2,678	93,490	$5,465	$8,143	$15,766

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10.0 CONCLUSIONS AND RECOMMENDATIONS

Initial study indicates that a long-life, reliable, and flexible resistojet assembly can be developed for Space Station at reasonable cost. The assembly incorporates resistojet thrusters, which are currently being designed for Space Station. The requirements for all of the fluid components, except for the water vaporizer, are similar to those on other Space Station systems; consequently, concept commonality should minimize development cost. The power controller also incorporates components that will be developed for other space station systems, thus reducing development and verification costs.

Recommended additional studies to be conducted prior to Phase C/D are as follows:

- Conceptual design and analysis of resistojet assembly
- Control system study
- Cost update

The conceptual design includes preparation of layout drawings of the assembly, both stored in the Space Shuttle and deployed. The drawings include component geometry and packaging, dimensions, structure, connections to the fluid storage and power systems, attachments, and shielding. The conceptual design includes flow, thermal, and structural analysis in support of the design.

The control system study includes the power control, fluid flow control, and health monitoring. Overall operational logic, sequencing time lines, transient effects, and interface parameters with the DMS, GN&C, and fluid storage system should be studied to further define a long-life, reliable, and cost-effective system.

Based upon the results of the first two tasks, the resistojet assembly cost estimates should be updated.

APPENDIX

PRELIMINARY SPECIFICATION FOR THE RESISTOJET ASSEMBLY FOR SPACE STATION

SPECIFICATION FOR RESISTOJET ASSEMBLY PROPULSION MODULE

1. SCOPE

This specification establishes the requirements and the test and verification methodology for these requirements for the resistojet assembly for the Space Station. The test and verification methodology covers all phases of the program, i.e., development, qualification, acceptance, integrated systems, prelaunch checkout and flight/mission operations.

2. APPLICABLE DOCUMENTS

2.1 Government Documents - The following documents of the exact issue shown form a part of this specification to the extent specified herein. The effective issue of those documents not specifically identified by change letter or date shall be the latest issue in effect on the date of contract. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of this specification shall be the superseding requirement.

SPECIFICATIONS

MIL-P-116H (1)	Preservation, Methods of
MIL-P-45213D (1)	Preservation and Packing of Rocket and Missile Systems Equipment for Shipment

STANDARDS

MIL-STD-130F (Notice 1)	Identification Marking of U.S. Military Property
MIL-STD-143B	Standards and Specifications, Order of Precedence for the Selection of
MIL-STD-419C	Cleaning and Protecting Piping, Tubing, and Fittings for Hydraulic Power Transmission Equipment
MIL-STD-461B	Electromagnetic Emission and Susceptibility Requirements for Control of Electromagnetic Interference
MIL-STD-704D	Aircraft Electric Power Characteristics

STANDARDS (Continued)

MIL-STD-767C 2 June 1981	Cleaning Requirements for Special Purpose Equipment, Including Piping Systems
MIL-STD-889B	Dissimilar Metals
MIL-STD-975F	NASA Standard, Electronic/Electrical/ Electromechanical (EEE) Parts List
MIL-STD-1472C (Notice 2)	Human Engineering Design Criteria for Military Systems, Equipment and Facilities
MIL-STD-1522A (Notice 1)	Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems
MIL-STD-1540B	Test Requirements for Space Vehicles
MIL-STD-1546 12 February 1981	Parts, Materials and Processes, Standardization Control and Management Program for Spacecraft and Launch Vehicles
MIL-STD-1547 31 October 1980	Parts, Materials, and Processes for Space and Launch Vehicles, Technical Requirements for
MIL-STD-1568A	Materials and Processes for Corrosion Prevention and Control in Aerospace Weapon Systems

STANDARDS (Continued)

MIL-STD-1595A	Qualification of Aircraft, Missile & Aerospace Fusion Welders
MIL-STD-45662 (Notice 3) 14 December 1984	Calibration Systems Requirements

HANDBOOKS

MIL-HDBK-5D	Aerospace Vehicle Structures, Metallic Materials & Elements for
MIL-HDBK-17A-1	Plastic for Aerospace Vehicles, Reinforced Plastics
MIL-HDBK-17A-2	Plastic for Flight Vehicles Part 2 Transparent Glazing Materials
MIL-HDBK-23A	Structural Sandwich Composites
MIL-HDBK-217D	Reliability Prediction of Electronics Equipment

OTHER PUBLICATIONS

Accession No.	Document No.	
J8400001	JSC 30000	Product Assurance Requirements for the Space Station Program

OTHER PUBLICATIONS (Continued)

Accession No.	Document No.	
	KHB 1700.7	Space Transportation System, Payload, Ground Safety Handbook
J8400002	NHB 1700.7A	Safety Policy and Requirements for Payloads Using the STS
J8400003	NHB 8060.1B	Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments
J8400004	JSC 08060	Space Shuttle System Pyrotechnic Specification
J8500005	JSC07700	Space Shuttle System Payload Accommodation Handbook
J8400020	JSC 19649	Space Station Fracture Control Plan
J8400021	JSC-STD-20001	Orbital Debris Environment for Space Station
J8400040	NASA TM-82585	Natural Environment Design Criteria for the Space Station Program Definition Phase
J8400042	SP-R-0022A	General Specification - Vacuum Stability Requirements of Polymetric Material for Spacecraft Application

OTHER PUBLICATIONS (Continued)

Accession No.	Document No.	
J8400043	MSFC-STD-522A	Design Criteria for Controlling Stress Corrosion Cracking
	NASA TM-86460 Rev. 1	Environmental Considerations Design Criteria for the Space Station Program Definition Phase
	NASA-TM-86498	Natural Environment Design Criteria for Space Station Definition and Preliminary Design
	JSC 19649	Space Shuttle Fracture Control Plan
	JSC 20149	General Specification, Space Station Requirements for Material Processing
	JSC 30203	On Orbit Maintenance Operations Plan
	JSC 30207	NASA Integrated Logistics Support (ILS) Plan
	JSC 30209	Combined Level A/B Software Management Plan
	JSC 30213	Space Station Program Design Criteria and Practices
	NASA SP-8013	Environment, Meteoroid Model

OTHER PUBLICATIONS (Continued)

Accession No.	Document No.	
	FED-STD-102B	Preservation, Packaging and Packing Levels
	MSFC-SPEC-504	Welding, Aluminum Alloys
	MSFC-SPEC-506	Standard Materials and Processes Control
	MSFC-SPEC-522	Stress Corrosion Control
	MSFC-SPEC-560	Welding Steels, Corrosion and Heat Rejection
	MSFC-STD-655	Weld Filler Materials, Control of
J8400041	MSFC-STD-5068	Standard Materials and Process Control
	MSFC-85M03892BB	Electronic/Electrical/Electromechanical Selection and Control Requirements, Space Shuttle Main Engine
J8400087	NASA-TM-82478	Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development
	DOD-STD-2167 4 June 1985	Defense System Software Development

2.2 Nongovernment Documents - The following documents form a part of this specification to the extent specified in Sections 3, 4, and 5. The effective issue of those documents not specifically identified by change letter or date shall be the latest issue in effect on the date of contract. In the event of conflict between the documents referenced herein and the content of this specification, the content of this specification shall be the superseding requirement.

SPECIFICATIONS TBD
STANDARDS TBD
OTHER PUBLICATIONS TBD

3. REQUIREMENTS

3.1 Item Definition

3.1.1 General Description - The main purposes of the Space Station propulsion system are altitude maintenance, reaction control/attitude control, and collision avoidance. The resistojet has the unique ability to provide thrust for the altitude maintenance function (atmospheric drag makeup) while disposing of a wide variety of excess fluids expected to be present on board Space Station. The resistojet propulsion system is a low-thrust (approximately 100 millipounds) supplement to a high-thrust (approximately 25 pounds) propulsion system. The high-thrust system will be required to perform all reaction control/attitude control functions, including collision avoidance, and to perform altitude maintenance requirements not provided by the resistojet system.

3.1.2 Mission - The resistojet assembly shall provide the capability of disposing of the Space Station waste gases and waste water.

3.1.3 Operational Concepts - The resistojet assembly launch package shall perform (1) ground operations to ensure STS interface compatibility, (2) launch operations mounted in flight support equipment in the orbiter bay, and (3) assembly on-orbit and associated checkout. The resistojet assembly shall operate in orbit as specified in 3.2.1.5 under the conditions specified in 3.2.7.

3.1.4. Major Assembly List - The resistojet assembly shall consist of the items listed in the following subparagraphs:

3.1.4.1 Resistojet Subsystem Assemblies - TBD

3.1.4.2 Integration Hardware - TBD

3.1.4.3 Government-Furnished Property - TBD

3.1.5 Software Items - TBD

3.2 Characteristics and Requirements - TBD

3.2.1 Performance - TBD

3.2.2 Physical Characteristics

3.2.2.1 Location - TBD

3.2.2.2 Operating Envelope - TDB Axis

3.2.4 Reliability - (TBD) Refer to 6.1.1.

3.2.4.1 Maintainability - The resistojet assembly shall be maintainable in orbit. Refer to 6.1.2.

3.2.4.2 Maintenance - Maintainability provisions shall ensure that all non-emergency maintenance shall be performed with the beta joint deactivated and with the PV array oriented between 90 to 180 degrees away from the sun.

3.2.4.3 Orbital Replaceable Units (ORU) - All ORUs shall be replaceable with the use of EVA or remote maintenance. ORUs shall be designed to be removed and replaced without removing other ORUs where practical. Each ORU shall be operationally verifiable.

3.2.4.4 Fault Detection - The resistojet assembly shall provide for remote fault detection and fault isolation.

3.2.5 Availability - The minimum availability requirement for the resistojet assembly shall be TBD.

3.2.5.1 Service Life - The resistojet assembly shall have the capability to remain operational indefinitely through periodic inspection, maintenance, and replacement of components.

3.2.5.2 Storable Life - The resistojet assembly shall have a storage life of TBD years.

3.2.6 Safety - (TBD) Refer to 6.1.3.

3.2.6.1 Hazard Analysis - The Contractor shall perform hazard analyses to identify known and potential hazards, establish preventive measures, and provide for verification that each hazard has been eliminated, controlled, or reduced to the level of an acceptable risk.

3.2.6.2 Safe Temperatures - Astronauts shall not be exposed to any surfaces greater in temperature than 235 F. All exposed surfaces shall be less than this temperature during normal operation.

3.2.7 Environment - The resistojet assembly shall meet the performance requirements of 3.2.1 after and during exposure to the following natural and induced environmental conditions.

3.2.7.1 Natural Environment - The resistojet assembly shall be designed to withstand the natural environmental conditions specified in NASA-TM-86498 and the following subparagraphs.

3.2.7.1.1 Altitude - The resistojet assembly shall be designed to operate in a low earth orbit. The altitude will vary from 180 nmi to 250 nmi.

3.2.7.1.2 Meteoroids - The resistojet assembly shall be designed for protection against micrometeoroids. The micrometeoroid model provided in NASA TM 82478 and SP8013 shall be used. Micrometeoroid protection shall be specific to the assembly as follows: TBD

3.2.7.1.3 Atomic Oxygen - Component hardware and structures which are directly exposed to the low earth orbit atomic oxygen (AO) environment shall be designed to meet the service life requirements while being subjected to a constant atomic oxygen flux of 1.5×10^{14} atoms/cm^2-sec.

3.2.7.1.4 Vacuum and Outgassing - The vacuum environment and outgassing caused by the natural environment will be as specified in SP-R-0022.

3.2.7.1.5 Ground Conditions - The resistojet assembly shall be capable of withstanding the following natural ground environmental conditions:

- Humidity: (TBD)
- Temperature: (TBD)
- Dust (TBD)

3.2.7.2 Induced Environment - The resistojet assembly shall be designed to withstand induced environmental conditions including electromagnetics, vibration, acoustics, shock, temperature, reduced atmosphere, contamination, and radiation under checkout, launch, and orbital conditions, as specified in NASA TM-86460 and JSC 07700.

3.2.8 Transportability - The resistojet assembly shall be capable of being transported, using normal transportation methods, to required assembly, test, and launch facilities. Hardware shall be transported and packaged such that the transport does not impose more stringent requirements on the flight hardware than the flight environment.

3.2.8.1 Launch . The resistojet assembly and its components shall be capable of withstanding the expected launch conditions specified in JSC 07700.

3.2.8.2 Ground Handling - The resistojet assembly shall be capable of withstanding the maximum G factor that will be encountered during ground handling of 1.5 G.

3.2.8.3 Space Transportation System (STS) - The resistojet assembly shall be capable of being packaged in and launched on the STS. All ORUs must fit up with the provided launch cradles or pallets.

3.2.9 Storable - Items shall be stored in a controlled and sheltered environment and shall be compatible with the preservation methods of MIL-P-116 to the appropriate level specified in FED-STD-102 so that protection may be provided during storage.

3.2.10 Software Performance Requirements - Except where superseded by other governing documents, software performance shall be in accordance with the standards specified in DOD-STD-2167.

3.2.10.1 General Description - Software shall be defined to mean all sets of associated computer instructions and computer data definition, in any language, written to enable any processor hardware to perform computation or control functions for the operation or support of the Space Station and its development. It also includes all data, listings, and associated documentation. Also, for the purposes of this document, and in accordance with JSC 30209, the term software will include any firmware that is under Space Station configuration control. Firmware is considered to be code or data loaded in a class of computer memory that cannot be dynamically modified during processing. The Space Station resistojet assembly electrical power system software shall consist of two general categories: (1) station flight software and (2) station support software. These two categories are further divided as indicated in the following subsections.

3.2.10.2 Flight Software - Resistojet assembly flight software shall consist of all programs operating on those processors that are required to operate the assembly onboard the Space Station. It includes all software and firmware developed by the Contractor for control and data management in connection with the resistojet assembly.

3.2.10.2.1 Flight Software Requirements

a. The flight software shall execute on a set of processors configured to provide a hierarchal control structure, with the processors in each level providing control over an increasingly narrow subset of the entire system.

b. It shall be possible to make on-orbit upgrades or modifications to software loaded in volatile memory without interruption of normal resistojet assembly operations.

c. All flight software shall be written in Ada and translated into executable code using a certified Ada compiler.

d. The software shall execute on one of the station standard data processors (SDPs).

3.2.10.2.1.1 Quality Factors - All resistojet assembly flight software shall:

a. Be designed in a structured format, with all programs divided into modules of generally no more than 100 executable lines per module.

b. Utilize memory space such that it is possible to load a new version of an existing program onto the operating processor without interfering with the execution of the current software.

c. Undergo quality evaluation as specified in DOD-STD-2167.

3.2.10.3 Support Software - Support software shall constitute all software written or obtained to function in a supporting role for the operation, development, test, or validation of the station flight software. It will generally not be resident on any processor that is physically onboard the station, but is anticipated being utilized on ground support computers exclusively.

3.2.10.3.1 Operational Support Software - That body of software which will be utilized in ground monitoring of on-orbit EPS operations, prelaunch checkout, and on-orbit upgrades shall be defined as operational support software. It may include commercially available software as well as programs written specifically for the Space Station project. All operational support software shall:

a. Be specified, monitored, and subject to controls appropriate with its rating for man- or mission-criticality in accordance with the category designations specified in the NASA Lewis Research Center Space Station Software Management Plan.

b. Be written in Ada and translated into executable code using a certified Ada compiler.

3.2.10.3.2 Development Support Software - That body of software which will be utilized in support of software design, coding, and testing functions is defined as development support software. All development support software shall:

a. Conform to applicable standards established for the Space Station software support environment (SSE).

b. Execute on standard support environment host computers.

3.2.10.3.2.1 Software Support Environment - The station software support environment (SSE) will consist of all software tools, and simulations, that will be used in any phase of the development of flight software, or operational support software, for the station project in general. It is anticipated that many of the necessary tools and simulators will be provided as part of the program-wide SSE being coordinated by NASA. Wherever possible, software development tools shall be from the SSE to provide program-wide uniformity of documentation and approach.

3.2.10.3.1.2 Interim SSE - Should portions of the general SSE not be ready for site utilization when needed, then the local site shall generate or otherwise obtain necessary software tools as part of an interim SSE. Those portions of the SSE that are available shall be used where appropriate, and any interim tools shall be phased out as standard counterparts become available.

3.2.10.4 Software Operational Environment - All software specified herein shall execute on one of the standard host computers designated as a component of the SSE. Additional requirements shall apply to flight software.

3.2.10.4.1 Flight Software Operational Environment - The environment of 3.2.10.4 shall be considered an intermediate requirement for the test and demonstration of flight software during development. The final operational environment shall be one of the Space Station SPDs, selected to provide adequate computational capability and memory storage for the software to meet the requirements of 3.2.10.5.

3.2.10.4.2 Support Software Operational Environment - The support software shall operate on one of the standard host computers designated as a component of the station SSE.

3.2.10.5 Software Functional Requirements - General functional requirements for the resistojet assembly software are:

a. The resistojet assembly software shall provide overall control of the hardware and associated functions for resistojet assembly operation.

b. Based on data exchanged with guidance navigation and control (GN&C), the resistojet assembly software shall coordinate the waste disposal of the FMS.

c. The resistojet assembly software shall support sensor monitoring, data reduction, and data transfer for status reporting, health monitoring, and self-diagnosis.

3.2.10.5.1 Resistojet Assembly Controller Software - The software executing on the resistojet assembly shall be part of the FMS software hierarchy.

3.2.10.5.2 Individual Component Software - Software loaded onto local embedded processors, or firmware resident on component programmable read only memories (PROMS), shall conform to the general requirements for redundancy, reliability, and documentation.

3.3 Design and Construction Standards

3.3.1 Specifications and Standards - All specifications and standards shall be selected in accordance with MIL-STD-143. Electrical/Electronic/Electromechanical (EEE) part shall be in accordance with MSFC-85M03928 (JAN Class "S" or JAN Class "B") and MIL-STD-975 (Appendix B) as applicable or MIL-STD-1546 and MIL-STD-1547 as applicable.

3.3.2 Materials, Processes, and Parts - MIL-HDBK-5, MIL-HDBK-17, MIL-HDBK-23, shall be used for selection of materials covered therein.

3.3.2.1 Hazardous Materials - The requirements for hazardous materials shall be as follows:

a. General - The use of hazardous materials shall be minimized; those used shall meet the applicable requirements specified in NHB 8060.1.

b. Material Radiation Effects - Materials and components subject to insidious degradation in Space Station ionizing environment shall not be used where that degradation can cause or contribute to any personnel hazards or reduce component life expectancy.

c. Mercury - The use of mercury or its compounds shall be restricted.

3.3.2.2 Structure - The resistojet assembly structural requirements shall be as follows:

a. Structural materials shall be resistant to damage from impact by both micrometeoroids and space debris. The meteoroid model is defined in SP-8013, and NASA TM-82585. The orbital debris environment is defined in JSC 20001. Penetration of any pressurized component shall not cause loss of pressure capability in adjacent elements.

b. All structures shall have positive margins of safety (MS) for all load conditions. The following equation defines MS:

$$MS = \frac{\text{Allowable Load}}{\text{Limit Load x Factor of Safety (FS)}} - 1.0$$

Note: Factors of safety are assumed multiplicative constants applied to maximum expected or limit loads that occur during any phase of the hardware from manufacture throughout its operational life to account for uncertainties in load definition, material properties, dimensional discrepancies, etc.

c. The structure materials shall have appropriate fracture control requirements as defined in JSC-19649.

d. The primary, secondary, and transport structure shall be designed so that failure of a single structural member shall not degrade strength or stiffness to the extent that the crew or mission is placed in jeopardy, or shall not result in a catastrophic failure.

3.3.2.3 Margins and Factors of Safety - For applications involving structures and pressure vessels, the following definitions shall apply:

a. Limit Load - The maximum load expected on the structure during mission operation including NSTS intact abort.

b. Ultimate Factor of Safety - The factor by which the limit load is multiplied to obtain the ultimate load.

c. Ultimate Load - The product of the limit load multiplied by the ultimate factor of safety.

d. Allowable Load - The maximum load which the structure can withstand without rupture or collapse.

e. Maximum Operating Pressure - The maximum pressure applied to the pressure vessel by the pressurizing system with the pressure regulators and relief valves at their upper limit, with the maximum regulator fluid flowrate, and including the effects of system environment such as vehicle acceleration and pressure transients.

f. Proof Pressure - The pressure to which production pressure vessels are subjected to fulfill the acceptance requirements of the customer to give evidence of satisfactory workmanship and materials quality. Proof pressure is the product of maximum operating pressure times the proof factor.

g. Margin of Safety - The ratio of allowable load to ultimate loud minus one.

h. Safe Life - A design criterion under which failure will not occur because of undetected flaws or damage during the specified service life of the vehicle; also, the period of time for which the integrity of the structure can be ensured in the expected operating environments.

3.3.2.4 Allowable Mechanical Properties - Values for allowable mechanical properties of structural materials in their design environment, e.g., subjected to single or combined stresses, shall be taken from MIL-HDBK-5, MIL-HDBK-17, MIL-HDBK-23, or other sources approved by NASA. Where values for mechanical properties of new materials or joints or existing materials or joints in new environments are not available, they shall be determined by analytical or test methods approved by NASA. When using MIL-HDBK-5, material "A" allowable values shall be used in all applications where failure of a single load path would result in loss of vehicle structural integrity. Material "B" allowable values may be used in redundant structure in which the failure of a component would result in a safe redistribution of applied loads to other load-carrying members.

3.3.2.5 Fatigue - Safe-life design shall be adopted for all major load-carrying structures. These structures shall be capable of surviving without failure a total number of mission cycles that is a minimum of four times greater than the total number of mission cycles expected in service (shown by analysis or by test through a rationally derived cyclic loading and temperature spectrum). This does not preclude fail-safe structural features.

3.3.2.6 Creep - The design shall preclude cumulative creep strain leading to rupture, detrimental deformation, or creep buckling of compression members during their service life. Analysis shall be supplemented by test to verify the creep characteristics for the critical combination of loads and temperatures.

3.3.2.7 Thermal Distortion - The effects of thermal distortions in the structure shall be included, where applicable, in interface specifications, analyses of attached systems, and deformation analyses such as loads and pointing analyses. The design of the primary structure shall minimize the effects of thermal distortions on other systems.

3.3.2.8 Materials - Materials shall comply with MSFC-STD-506B and shall be selected on the basis of functional acceptability and suitability, extended life, technological maturity, manufacturability, inspectability, contamination characteristics, specific strength, compatibility, availability, cost, and safety. Material selection documentation requirements are defined in JSC 20149.

3.3.2.9 Welding - Weld joints shall be designed to satisfy the reliability, maintainability, environmental, safety structure, and leakage constraints of JSC 19649, JSC 30213, MSFC-SPEC-504, MSFC-STD-506, MSFC-SPEC-560, MSFC-STD-655 and MIL-STD-1595.

3.3.3 Contamination Control

a. Materials Contamination - Equipment or materials sensitive to contamination shall be handled in a controlled environment. Fluids and materials shall be compatible with the combined environment in which they are employed.

   1) Materials exposed to space vacuum shall meet the requirements of SP-R-0022, for vacuum outgassing.

   2) Exterior materials shall consider atomic oxygen effects, as specified in 3.2.7.1.4.

b. Corrosion Prevention and Control - Materials, processes, and protective treatments shall be in accordance with MIL-STD-1568, excluding sections peculiar to corrosion control technical order. The use of dissimilar metals shall be in accordance with MIL-STD-889. Stress corrosion control shall be as specified in MSFC-STD-522.

c. Cleanliness - The surfaces which contact system pressurrants shall be clean in accordance with MIL-STD-419, MIL-STD-767 and MIL-STD-1522.

3.3.4 Interchangeability and Replaceability - All replaceable parts or assemblies having the same part number shall be directly and completely interchangeable with respect to installation and performance. The replacement of interchangeable parts or modules, as applicable, shall require a minimum of mechanical realignment or replacement of mating or adjoining assemblies. Interchangeability requirements shall not apply to permanent assemblies such as welded, potted, encapsulated, or matched detail parts.

3.3.5 Identification and Marking - Items shall be identified and marked in accordance with MIL-STD-130. Paper decals and rubber stamping shall not be used for equipment labeling.

3.3.6 Workmanship - The resistojet assembly shall be fabricated and finished in a thorough, workmanlike manner. Particular attention shall be given to freedom from blemishes, defects, burrs, and sharp edges; accuracy of dimensions and radii of fillets; marking of parts; thoroughness of cleaning; neatness of welding, riveting, surface finishes, and wiring alignment of parts; tightness of threaded fasteners; and thoroughness of mechanical fastener and local wire assemblage.

3.3.7 Human/Robotics Performance and Engineering - The use of teleoperator or robotic devices shall be considered in the design. Partitions, walls, and closeout structure, as appropriate, shall be designed to be arranged on-orbit to accommodate Space Station growth, maintenance, and access to power distribution items. The connections of power distribution items residing in and attached to secondary structure shall be designed to be made and broken with minimal crew effort and time. Attached hardware shall permit relatively easy equipment reconfiguration. The resistojet assembly shall comply with the general requirements for controls, labeling, work space, design requirements, maintainability, hazards, and safety criteria specified in MIL-STD-1472.

3.4 Logistics

3.4.1 Maintenance - The resistojet assembly shall be designed to be maintained at the levels specified in JSC 30203 and JSC 30207.

3.4.2 Supply - A program for supply support shall be planned that will ensure system availability. All levels of maintenance shall be supported with spare ORUs in a manner that provides support of operational time constraints, ensures timely recycle of failed items to serviceable stocks, and accomplishes this support at minimum practical risk and cost.

3.5 Personnel and Training - Logistics support shall be provided for training operational and maintenance personnel and for providing training equipment needed to support the Space Station program through its life cycle. Logistics requirements shall be provided for integration into the flight crew training. Personnel and training shall include, but not be limited to, the following functional activities:

a. Development of personnel training plan

b. Defining training equipment and devices

c. Production of training data and equipment hardware and software

d. Identification of personnel and skill level requirements

e. Identification of skill level and training requirements for ground-based organizational intermediate and depot level maintenance

f. Identification of the on-orbit skills and training requirements for on-orbit organizational and intermediate level maintenance

3.6 <u>Interface Requirements</u> - Interfaces between the resistojet assembly and the other work packages shall be as specified in TBD. The interfaces are at the subsystem and work package level. Refer to 6.1.4.

4. VERIFICATION

4.1 General - Inspections that consist of examinations, demonstrations, tests, and analyses shall be conducted during the design and development to provide assurance of compliance with the requirements of this specification. Proof of meeting the quality conformance inspections as specified herein shall constitute qualification. Data and test results from development, integrated tests, and prequalification programs shall support analyses herein for formal qualification. These programs shall be as follows:

a. Development Tests - The suitability of the resistojet assembly for use on the Space Station by means of ground-level tests shall be verified by development tests. These tests may be conducted at the component level.

b. Integrated System Test - Integrated tests shall be conducted using a test configuration formed by combining one or more portions of the resistojet assembly.

c. Pre-Qualification Program - The pre-qualification program shall be structured to demonstrate compliance with resistojet assembly requirements.

4.1.1 Responsibility for Verification - The Contractor shall be responsible for the performance of all inspections in accordance with this specification. The procuring activity reserves the right to perform any of the specified inspections at the Contractor's site or other sites.

4.1.2 Verification Methods - Qualification shall be by similarity, analysis, inspection, demonstration, and/or test as defined in TBD which shows the relationship between the Section 3 requirements and the verification requirements of Section 4 of this specification.

4.1.2.1 <u>Verification Definition</u> - Similarity, analysis, inspection, demonstration, and test shall be as follows:

a. <u>Similarity</u> - A component may be verified by similarity if the same part has been qualified for a similar application. If all of the requirements have not been verified in this prior verification, it shall only be necessary to demonstrate these deficiencies.

b. <u>Analysis</u> - Verification by analysis shall be the process of utilizing analytical techniques to verify that performance and/or environmental requirements are satisfied. Verification through analysis shall be used when verification by test is not possible, when test introduces significant risk into the resistojet assembly, or when analysis is an appropriate, cost-effective method of verification. In order for a requirement to qualify for verification by analysis, all of the following criteria shall be satisfied:

1) Verification by inspection is inadequate.

2) Verification by similarity is applicable.

3) Verification by test carries high risk of damage/contamination of flight hardware.

4) Analysis techniques that are rigorous and well understood are available.

5) Verification by test is not feasible and/or cost effective.

6) Analysis models shall be well known or verified by test data.

c. Inspection - Inspection shall be an element of verification consisting of investigation, without the use of special laboratory requirements, and shall be generally nondestructive and shall include (but not be limited to) visual inspection, simple physical manipulation, gauging, and measurement.

d. Demonstration - Demonstration shall be an element of inspection that is limited to readily observable functional operation to determine compliance with requirements. This element of inspection does not require the use of special equipment or sophisticated instrumentation.

e. Test - Test shall be an element of inspection that employs technical means including (but not limited to) the evaluation of functional characteristics by use of special equipment or instrumentation, simulation techniques and the application of established principles and procedures to determine compliance with requirements. The analysis of data derived from test shall be an integral part of this inspection.

4.1.3 Relationship to Management Reviews - To support the several management reviews, the requirements specified herein shall have been demonstrated to the extent defined below.

a. Preliminary Design Review

1) Similarity - Generic test data shall have been validated and the delta qualification program defined.

2) Analysis - Preliminary analyses validating the capability of the item to fulfill the requirements specified herein shall have been completed.

b. <u>Critical Design Review</u>

1) Similarity - Sufficient development tests shall have been conducted to demonstrate the capability of satisfactorily completing the delta qualification program.

2) Analysis - The preliminary analyses shall have been updated utilizing development test data.

3) Inspection - All components tested shall have been inspected and verified to meet the design requirements.

4) Demonstration - Those requirements that are to be verified by demonstration shall have been demonstrated utilizing development hardware representative of the flight hardware or suitable simulators.

5) Test - Sufficient development tests shall have been completed to demonstrate capability to meet the requirements herein.

c. Final Qualification Review

1) Similarity - All of the delta qualification testing shall have been completed.

2) Analysis - All analyses shall have been completed utilizing data from the appropriate development and qualification test programs.

3) Inspection - All hardware and software utilized in the qualification program shall have been verified to conform to all of the design requirements.

4) Demonstration - Those requirements that are to be verified by demonstration shall have been validated utilizing development hardware or simulators representative of the flight hardware.

5) Test - All delta qualification and qualification testing shall have been completed.

4.1.4 Test and Equipment Failures - The design of each test article shall include a failure mode and effects analysis and maintenance analysis. These analyses shall include limits and resulting disposition of test results and test articles. Any failure that occurs outside of these limits shall be handled in accordance with the Contractor's approved Failure Analysis and Reporting System and the NASA Problem Reporting and Corrective Action System.

4.1.5 Verification of Unplanned Equipment Uses - Equipment shall be used for performing the specific tasks for which it was designed and validated. Any other usage requires approval of the configuration control board per the Configuration Management Plan No. (TBD) and subsequent formal validation for this new usage.

4.2 Verification Requirements

4.2.1 Hardware Verification

4.2.1.1 Development - Sufficient tests shall have been conducted during the development phase of the program to demonstrate the capability of the selected design to meet all design requirements. These tests are shown in the Test and Verification Plan No. (TBD).

4.2.1.2 Qualification - The tests to demonstrate that the resistojet assembly will meet its performance and design requirements under the anticipated operations environments are shown in TBD.

4.2.1.3 Acceptance Test - The tests which will demonstrate that the resistojet assembly is ready for acceptance by the government are shown in TBD.

4.2.1.4 Integrated Systems - The tests that demonstrate that the resistojet assembly, when integrated with other elements of the Space Station, will meet the mission requirements, and that the physical functional and operational interfaces are compatible, are shown in TBD.

4.2.1.5 Prelaunch Checkout - The tests to demonstrate launch readiness are shown in TBD.

4.2.1.6 Flight and Mission Operation - The tests to verify that the resistojet assembly is only for on-orbit activation are shown in TBD.

4.2.1.7 Postflight - Since the only time an EPS component/subsystem will be replaced is in the event of a failure, no postflight tests are planned. The tests to be conducted will be defined in the failure analysis plan and will be developed on an individual basis.

4.2.2 Software Verification

4.2.2.1 General - Verification of operational software compliance with system design and operational requirements shall take place at every stage of software development in accordance with the NASA Lewis Research Center Space Station Software Management Plan. As applicable, software verification shall be by formal inspection and/or testing, with each development stage terminated with the reviews delineated in 4.2.2.3. Test plans, reports, and other documentation shall be prepared and submitted in accordance with a LeRC-approved Test and Verification Plan.

4.2.2.2 Testing

4.2.2.2.1 Development Testing - Verification of the proper function of coded software units during the development phase shall be by operational testing on the host development computer, with test results documented in accordance with the Test and Verification Plan.

4.2.2.2.2 Integration Testing - Verification of the proper function of coded software during the integration phase shall be by operational testing on the target processor, utilizing a mix of hardware and software simulations for any portions of the complete system that are not physically connected to the test configuration.

4.2.2.3 Reviews - All operational software shall be subject to a series of formal reviews. These shall be in accordance with the LeRC Software Management Plan, and, for each program identified as a Computer Software Configuration Item (CSCI), shall include the following:

a. System Software Requirements Review
b. CSCI Requirements Review
c. Preliminary Design Review
d. Critical Design Review
e. First Article Configuration Inspection
f. Customer Inspection
g. CSCI Test Review (Software System Test Review)
h. CSCI Acceptance Review

4.2.2.4 Formal Verification - Formal verification shall occur for all deliverable software prior to the final acceptance review. Corresponding documentation shall be in accordance with the Test and Verification Plan.

4.2.2.5 Independent Validation - Independent Verification and Validation (IV&V) shall be applied to those software units designated by LeRC by an activity separate from the software development activity.

4.2.2.6 Qualification - Qualification of any CSCI for flight readiness shall be by formal qualification testing in accordance with the Test and Verification Plan.

4.2.2.7 Acceptance - Conclusion of qualification testing and completion of the acceptance review shall constitute NASA acceptance of the CSCI. Delivery shall be by means of a magnetic tape containing the source code, along with all associated documentation.

4.2.2.8 Prelaunch Checkout - Prelaunch checkout of all flight software shall be conducted prior to final preparations for launch. It shall consist of exercising the software in the target hardware in accordance with the Test and Verification Plan.

4.2.2.9 On-orbit - On-orbit checkout of software shall consist of exercising the built-in test functions that are in random access memory (RAM) and in read only memory (ROM), and shall be conducted whenever programs are reloaded, processors restarted, or upon command from the Station operations management system (OMS), via the DMS.

4.3 Verification Reference Index - The reference between the Section 3 requirements and the verification method is presented in TBD.

4.4 Test Support Requirements

4.4.1 Facilities and Equipment

a. Existing facilities and equipment within NASA or other government agencies and contractors will be utilized to the maximum extent practical.

b. Activation and operation plans involving test facilities and equipment, personnel, procedures, and safety requirements will be prepared in accordance with the requirements of the Test and Verification Plan.

c. Wherever feasible, the test facilities and equipment shall incorporate standard mechanical, physical, and utility interfaces to facilitate multi-facility compatibility and uniformity of test results.

d. All test equipment will be qualified and/or certified to ensure that no damage or degradation will be introduced into the hardware being tested. The test results shall not include test equipment error.

e. The accuracy of the test equipment and measuring instruments shall be verifiable and traceable to the National Bureau of Standards and shall have a current calibration certification period which is sufficient to ensure that the particular test will be completed within the calibration period. Calibration shall be performed in accordance with MIL-C-45662A.

4.4.2 Articles - The following test articles are required to support the test program: TBD

4.4.3 Interfaces - The hardware and software interfaces shall be verified in accordance with the ICD Program Plan (No. TBD).

5. PREPARATION FOR DELIVERY

5.1 Preservation and Packing - All resistojet assembly components to be shipped shall be prepared for shipment in accordance with MIL-P-45213.

6. NOTES

6.1

6.1.1 Reliability Program Plan - The contractor shall prepare a reliability program plan and implement a reliability program in accordance with the plan and the requirements of JSC 30000, Section 9. As a minimum, the reliability program, as defined in the plan, shall utilize traditional analyses (FMEAs, CILs, redundancy studies, trade studies, etc.) to provide a support structure for the accomplishment of design objectives and development planning. Existing numerical data bases such as that of MIL-HDBK-217 shall be consulted in the preparation of numerical evaluations of component and system performance.

6.1.2 Maintainability Program Plan - The resistojet assembly shall be maintainable in orbit. A maintainability program in accordance with the requirements of JSC 30000, Section 9, shall be incorporated in the design. Maintainability considerations shall be incorporated as an integral part of the functional and spatial constraints for the work package element. Maintainability requirements shall be incorporated in the resistojet assembly design.

6.1.3 Safety Program Plan - A safety program shall be planned and implemented. A safety program plan that satisfies the requirements of JSC 30000, Section 9, and embodies the requirements of NHB 1700.7 and KHB 1700.7 shall be prepared.

6.1.4 Interface Control Program Plan - An overall interface control program plan shall be developed. The plan shall contain the following:

a. Interface control program procedures and responsibility
b. Preparation of requirements for ICDs
c. Technical description of interfaces

    1) Hardware interfaces
    2) Software interfaces

6.2 Acronyms

BOL - beginning of life
CEI - contract end item
CPU - computer processing unit
CSCI - computer software configuration item
DMS - data management system
EDAC - error detection and correction
ESA - European Space Agency
GFP - government furnished property
GN&C - guidance, navigation, and control
ILS - integrated logistics support
I/O - input/output
IOC - initial orbital configuration
HOL - higher order language
JEM - Japanese engineering module
JSC - Johnson Space Center
KSC - Kennedy Space Center
MSFC - Marshall Space Flight Center
MTB - mean time between failures
MTTR - mean time to repair
ORU - orbital replacement units
PROMS - programmable read only memories
PS - power source processor
RBI - remote bus interface (units)
RPC - remote power control (unit)
SDP - standard data processor
SSE - software support environment
SSU - sequential shunt unit
STS - space transportation system
TBD - to be determined
WP - work package

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15. Supplementary Notes

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16. Abstract

An initial study of the resistojet assembly was conducted. Preliminary design requirements were established based upon initial technical requirements imposed by the results of NASA studies and Rocketdyne studies. The requirements are directed toward long life, simplicity, flexibility, and commonality with other Space Station components. The resistojet assembly is comprised of eight resistojets, fluid components downstream of the waste fluid storage system, a power controller, structure, and shielding. The assembly consists of two identical subassemblies, one of which is redundant. Each subassembly consists of four 500-W resistojets, series redundant latch valves, a power controller, a water vaporizer, two pressure regulators, filters, check valves, disconnects, fluid tubing, and electrical cables. All components are packaged at the end of the stinger aft of the JEM and Columbus modules. Different flow and power control methods were studied. A constant inlet pressure and a two-power setting controller were tentatively selected based upon simplicity and reasonably high specific impulse for the range of waste gas compositions that are anticipated. The constant pressure is supplied by pressure regulators. The two set point power control includes individual power supplies to each resistojet heater and water vaporizer. An embedded data processor, a multiplexer-demultiplexer, and a network interface unit that are standard Space Station components are included in the power controller. The total dry weight of the resistojet assembly is approximately 172 lb. The total cost for design, development, test, evaluation, qualification, and flight hardware is estimated to be $16 million.

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